Arnold Schwarzenegger
Governor

BASELINE DEVELOPMENT AND ESTIMATION OF CARBON BENEFITS FOR EXTENDING FORESTED RIPARIAN BUFFER ZONES IN TWO REGIONS IN CALIFORNIA

PIER FINAL PROJECT REPORT

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PUBLIC INTEREST ENERGY RESEARCH
"Research Powers the Future"

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the Measurement, Classification, and Quantification of Carbon Market Opportunities in the U.S.: California Component project (contract number 100-98-001) and the Carbon Sequestration in Vegetation in California project (contract number 500-99-013, WA no. 50), conducted by Winrock International. The report is entitled *Baseline Development and Estimation of Carbon Benefits for Extending Forested Riparian Buffer Zones in Two Regions in California.* This project contributes to the PIER Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier, or contact the Energy Commission at (916) 654-4628.

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Abstract

A measurement and monitoring activity was carried out to assess the relative biomass carbon storage potential of extending forested buffer zones by 200 feet (100 feet either side of existing regulations) at two study sites representing key timber production regions in California: Sierran mixed conifers at Blodgett Forest Research Station(BFRS) in the Sierra Nevada and coastal redwoods at Jackson Demonstration State Forest (JDSF). Each of these site assessments is presented as a specific and independent case study, and each reflects a unique set of conditions (e.g., species composition), which determines the response to different management practices. The assessments were based on a combination of existing field data from forest inventory plots gathered by the respective forest sites, new field measurements for missing components, empirical modeling, and data integration. Researchers estimated the changes in carbon stocks for baseline conditions (continued harvesting) and compared these to the carbon stocks from conserving the forests with no harvesting. Extension of riparian buffer zones can lead to estimated benefits of 1,100–1,200 tons of carbon (C) per kilometer (km) of stream (or 2.3–2.5 t C/hectare per year (ha.yr)) over 80 years in mixed Sierran conifer forests and 920–1,270 tons C per km of stream (or 1.5–2.1 t C/ha.yr) over 100 years in coastal redwood forests. The carbon benefit arises from the increased biomass in living and dead trees in the forest exceeding the carbon stored in wood products and logging slash. Additional environmental benefits would include habitat for wildlife, protection for fish breeding and migrating sites, and a reduction in runoff from the land.

Executive Summary

Objectives

A measurement and monitoring activity was carried out to assess the relative biomass carbon storage potential of extending forested buffer zones by 200 feet (100 feet either side of existing regulations) at two study sites representing key timber production regions in California: Sierran mixed conifers at Blodgett Forest Research Station(BFRS) in the Sierra Nevadas and coastal redwoods at Jackson Demonstration State Forest (JDSF). Each of these site assessments is presented as a specific and independent case study and each reflects a unique set of conditions (e.g., species composition), which determines the response to different management practices.

Figure S1. Location of Jackson Demonstration State Forest and Blodgett Forest Research Station in California

Outcomes

Blodgett Forest Research Station

Supplementary field measurements were made during October 2003 to allow data from the Blodgett Forest Research Station's (BFRS) network of permanent plots to be used for carbon analyses. Data from the permanent sample plots were converted to biomass carbon estimates in trees using regression equations available in the literature for Californian forests. Other data from the Blodgett forest plots were not directly usable for estimating carbon stocks. The additional data collected consisted of measurements to relate litter and duff depth and biomass, soil carbon stocks, and dead wood densities.

Analyses of the BFRS permanent plots alongside literature reports permitted the creation of growth curves. The plot data also resulted in relationships between forest age or aboveground biomass carbon and forest floor carbon, standing and lying dead wood and the carbon stocks belowground in roots. There was little relationship between forest age and soil carbon stocks and so soil carbon was emitted from this analysis.

Extension of riparian buffer zones from 75 feet (baseline) to 175 feet results in carbon storage *benefits* amounting to ~ 1,100–1,200 tons over the additional 6.1 hectares of riparian forest retained per straight line kilometer of stream length after 80 years. The additional carbon results from continued accumulation of forest carbon in the protected area compared with varying forest carbon in the managed (baseline) area due to successive harvests and regrowth and consequent reduction in equivalent long-term average forest carbon storage. The reduction in forest carbon on the managed site is not offset by cumulative carbon storage in long-term wood products.

Jackson State Demonstration Forest

Field data were collected at the JDSF in February 2004. Measurements were made of trees in and around clearcuts and group selections and of dead wood, litter, understory and soil carbon. The JDSF was dominated by redwood forests and activities focused in this forest type.

Growth curves for coastal redwood at JDSF were developed from existing empirical yield tables. Field measurements drove the calibration of models predicting the accumulation of dynamic forest carbon pools including litter and downed dead wood stocks. Standing dead wood, understory vegetation, and soil carbon showed no appreciable changes with management or stand age. These findings were used to predict responses in forest biomass with change in management practices. The transformation efficiency of receiving mills was substantiated via interviews with local operators.

Over one rotation of model scenarios involving different site productivities and initial stand ages, extension of riparian buffer zones from the existing mandate of 100 feet (baseline) to 200 feet either side of the watercourse, consistently results in an unambiguous increase in carbon storage. Over one rotation, carbon storage benefits resulting from extension of the buffer area range from 151 to 208 t C per hectare or 921 to 1,269 t C per one kilometer length of stream.

Average carbon storage in the baseline case, even including harvest-derived pools of slash and long term wood products, is easily exceeded by the steadily growing, unharvested, forest within the buffer extension area. In fact, the addition of post harvest slash and long-term wood products to carbon storage, which approaches an average of 110 t C/ha derived after 500 years, does not offset the reduction in long term average *forest* carbon storage accompanying management, ~ -300 t C/ha (~ 500+ t C/ha for a mature redwood stand on site index 160 *minus* the long term average of 193 t C/ha for the same redwood stand under even-aged management with a 90-year rotation). The extended buffer can thus potentially generate an increase in carbon storage that approaches 200 t C/ha on a time scale of hundreds of years.

Conclusions, Recommendations, and Benefits to California

Extension of riparian buffer zones by 100 feet in commercially managed forests in California can lead to estimated carbon benefits of 1,100 tons per km of stream over 80 years in mixed Sierran conifer forests and 920 tons per km of stream over 100 years in coastal redwood forests. Additional benefits to California will be in water quality, and in habitat for wildlife and fisheries.

The estimates provided here are assessments of the potential carbon benefits from extending riparian buffer zones. The report outlines details of the measurements and the types of analyses needed to calculate the carbon stocks under baseline and change-in-management conditions when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring. Where there are no existing inventory data, additional measurements would be required but the analyses would essentially be the same as those given here. In a separate report (*Methods for Measuring and Monitoring Forestry Carbon Projects in California*) we provide more details on the methodology for collecting the field data.

1.0 Introduction

The measurement and monitoring activity was carried out as two case studies from two regions of the State: the mixed conifer regions of the Sierra Nevada's and the coastal redwood / Douglas-fir forests of the north coast of California. This report serves to assess the relative biomass carbon storage potential of extending forested buffer zones at two study sites representing key timber production regions in California; Sierran mixed conifers at Blodgett Forest Research Station (BFRS) in the Sierra Nevada and coastal redwoods at Jackson Demonstration State Forest (JSDF).

The aim of the project was to provide an assessment of the carbon benefits for projects incorporating an extension of forested riparian buffers and to create measuring and monitoring plans for quantifying those benefits over time. Each of these site assessments is presented as a specific and independent case study and each reflects a unique set of conditions (e.g., species composition) that determines the response to different management practices.

Forest inventories exist in both BFRS and JSDF. The decision was taken that replicating the effort of the inventories given financial and temporal constraints would be fruitless. Consequently field effort was concentrated on factors necessary to convert each of the forest inventories into carbon inventories (e.g., litter biomass, dead wood density) and on factors missing from the inventories (e.g., soil analyses in both forest types and litter analysis at JSDF).

One of the major environmental issues currently pending in California is the restoration of salmonids and their habitat. This directly involves the intensity and extent of forest management in riparian zones within the State, and in particular, riparian zone management and road management are considered two key factors affecting habitat viability for salmonids. In response, the regulatory agencies, including the National Marine Fisheries Service, Environmental Protection Agency, State and Regional Water Quality Control Boards, Department of Fish and Game, and the State Board of Forestry and Fire Protection have increased timber harvesting restrictions in riparian zones. They have also extended some protection to watercourses not previously protected (seasonal and intermittent). The result is that there will be a significant increase in undisturbed forest, with attendant large old trees and woody debris, spread across the landscape.

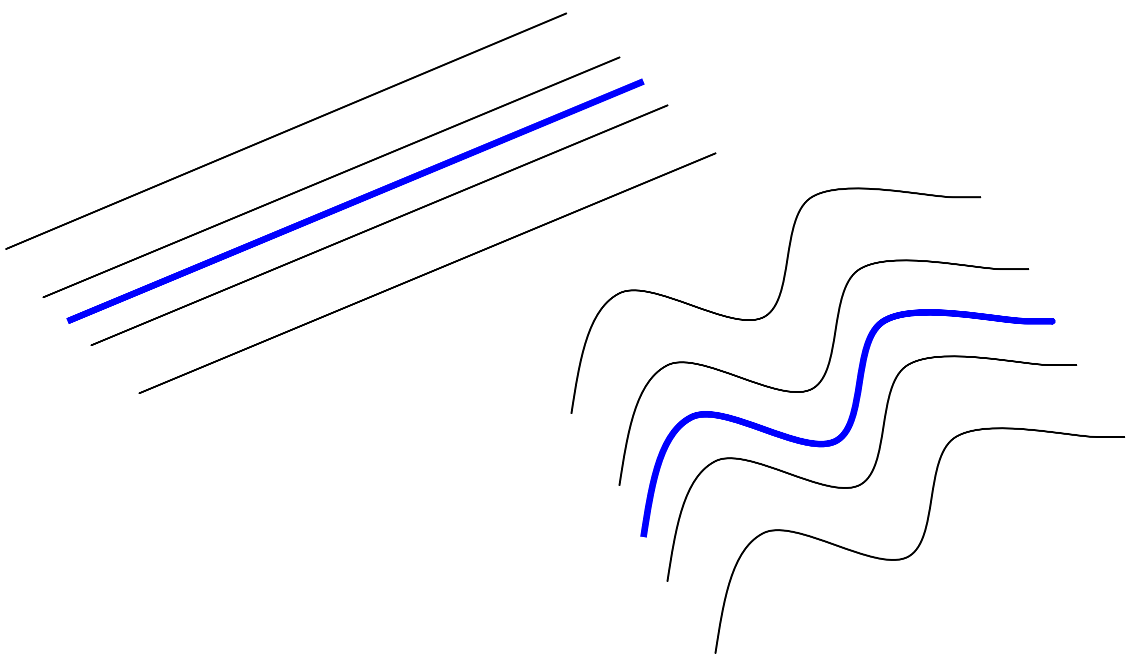
State Policy makers and land managers have developed an interest in providing incentives for landowners to protect riparian habitats. One means of doing this would be to provide the landowners value for the retention of greater forest area through the developing markets for carbon sequestration in forests. Estimation of carbon benefits for changes in management of riparian zone will provide some guidance for policy makers on what values may be available for landowners if carbon markets come to fruition.

Current legislation (California Department of Forestry and Fire Protection 2003) dictates Watercourse and Lake Protection Zones (WLPZ) on either side of Class I (fish-bearing) streams of no less than 75 and 100 feet either side, for sites with slopes of < 30% and sites with > 30% slopes, respectively. Within WLPZs, no less than 50% overstory must be retained. This effectively excludes the WLPZs from even-aged management. In practice, WLPZs tend to be kept free of all harvest by both state and private land managers (Marc Jameson 2004, CDF, pers. comm.), and thus in the model, no harvest of any kind takes place in the buffer. The width of

WLPZs may be insufficient to adequately remove runoff or to provide optimal conditions for aquatic and riparian species including amphibians and salmonid fish (Noss 2000; Ralph Tiner 2003, US Fish and Wildlife Service, pers. comm.). The analysis here considers a 100 foot extension to existing buffers on either side of the watercourse, amply affording the minimum 45 meters recommended by Brosofske et al. (1997). Buffers considered thus total 175 and 200 feet either side (53 to 61 meters) for slopes of < 30% and sites with > 30% slopes, respectively.

1.1. The with-buffer and without-buffer baselines

Here the carbon benefits of an extended forested buffer are analyzed in a Sierran Mixed Conifer (BFRS) and a Coastal Redwood (JDSF) situation. The carbon benefits will be examined only in the 100 feet extension to the buffer on either side of the stream. At BFRS, where slopes average < 30%, buffers are thus extended from the 75 feet mandate to 175 feet. At JDSF, where slopes average > 30%, buffers are extended from the 100 feet mandate to 200 feet. All analyses will be on a kilometer (0.62 miles) of modeled stream. A straight stream is considered as a representation of all forms of stream with the assumption that in any stream the turns can be canceled out to average a straight form (Figure 1.1).



100 ft extension = 30.48 m

30.48 m x 1000 m stream length = 3.05 ha on each side of the stream =total of 6.1 ha / km

Figure 1.1. The amount of land in the existing legislated buffer and the proposed extension. A straight length of stream here represents any form of stream.

1.2. Environmental co-benefits of extended riparian protection

Dead wood is a critical structural component of stream habitat. By providing a higher density and variety of forage and shelter opportunities, submerged dead wood can increase the capacity of streams to accommodate a higher diversity of aquatic life (Harmon et al. 1986), including economically important species like salmonid fish. The buffer zone extensions out to 175 and 200 feet will allow for additional dead wood input to streams through retention of trees 75 to 175 and 100 to 200 feet from the stream. As trees in California conifer forests often approach or exceed 150 feet in height at maturity, some of these trees, which would have otherwise been harvested, will contribute dead wood stocks to streams. Although the magnitude and frequency of the additional inputs will depend on the vagaries of natural tree fall, the increased source of inputs is clear.

Riparian buffers further offer accessible interior forest areas adjoining streams on which amphibians with aquatic and terrestrial life stages are dependent; current legally-mandated riparian zones offer only forest edge habitat (Noss 2000).

1.3. Leakage

Leakage occurs where the activities of a carbon project lead to carbon losses outside the borders of the project.

The possibility of leakage can call into question carbon benefits reported from a project. Projects should thus demonstrate that anticipated benefits do not result in increased emissions outside of the project area due to displacement of activities.

In terms of a change in forest management practices, leakage could result if a project results in decreased harvest accompanied by increased harvest and attendant emissions elsewhere to accommodate steady demand of timber. The increase in the width of the riparian buffer could lead to leakage as it involves a reduction in harvesting which could lead to additional harvesting elsewhere and consequently reduce the net carbon benefits of the buffer extension.

Current discussions of new variable retention requirements under California Forest Practice Rules call for exclusion of WLPZs (riparian buffers) from calculation of retention area for compliance (i.e., retention will be additional to buffers). Extended buffers thus will result in harvest reductions beyond state-mandated limits and their implementation could result in some leakage that will have to be considered in a full accounting of net carbon benefits.

1.4. References

California Department of Forestry and Fire Protection. 2003. California Forest Practice Rules. Title 14, California Code of Regulations Chapters 4, 4.5, and 10. State of California. 275 pp.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. In *Advances in Ecological Research* 15: 133–302.

2.0 Blodgett Forest Research Station

2.1. Background information

Blodgett Forest Research Station (BFRS) is situated in the Georgetown Divide in the Sierra Nevada mountains of California. The station predominantly consists of high site mixed conifer forest (Figure 2.1). The Michigan-California Lumber Company gifted the forest to the University of California in 1933 with the purpose of providing a research site and a site for the demonstration of practices to the public, industry and students of forestry (Olson and Helms 1996).

Figure 2.1. Mixed Sierran conifer forest at BFRS

The forest was harvested almost in its entirety in three entries in 1900, 1908, and 1912 then for approximately 50 years no large-scale commercial harvesting occurred as the forest regenerated (Olson and Helms 1996). The forest is now divided into 109 compartments (Figure 2.2) dedicated to various management schemes including clearcut (e.g., Figure 2.3), shelterwood, single-tree selection, variable retention, group selection and young and old-growth preserves.

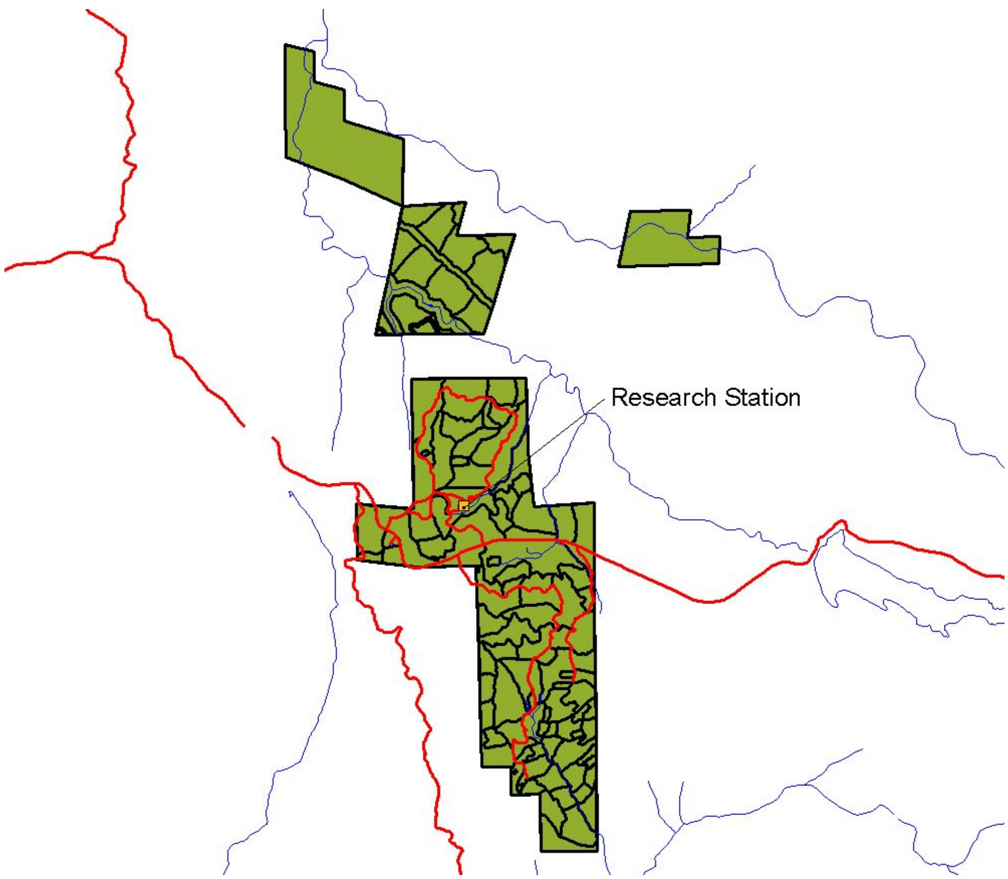


Figure 2.2. Blodgett Forest Research Station. The forest compartments are outlined.

A system of permanent, comprehensive forest inventory plots was started in 1974 and completed in 1980. The system consists of a six-chain (396 feet) grid of 1/10 acre plots. There are approximately 700 of these plots with additional plots in streams, group selections and other areas of special interest. During plots measurements (approximately every five years) a spectrum of environmental and physical data are collected including tree diameters and heights, dead wood measurements and depths of duff and litter (Olson and Helms 1996).

We visited BFRS in October 2003 to collect supplemental data required to increase the value of the Blodgett permanent plots for biomass estimations. Measurements were made to determine the relationship between litter/duff depth and biomass, dead wood volume and biomass and soil carbon storage.

The tree species commonly encountered at Blodgett are listed in Table 2.1.

Table 2.1. The tree species of BFRS. Commercially grown species are underlined.

Hardwoods	Conifers
Alder spp.	<u>Douglas Fir</u>
California Black Oak	<u>Giant Sequoia*</u>
Chinquapin	<u>Incense-cedar</u>
Dogwood	Lodgepole Pine
Canyon Live Oak	Nutmeg
Maple spp.	<u>Ponderosa Pine</u>
Pacific Madrone	<u>Sugar Pine</u>
Tanoak	<u>White Fir</u>
	Pacific Yew

Giant Sequoia is not native to BFRS, although it does occur naturally in the region.

Figure 2.3. Even-aged stands of ponderosa pine adjacent to BFRS

2.2. Carbon calculations for Blodgett forest

2.2.1. Estimating carbon components

2.2.1.1. Aboveground live biomass

Aboveground biomass can be estimated using the permanent plot data from Blodgett forest or similar forest inventory data. In this study even-age plots were selected representing the full range of ages available at Blodgett (very young to fully mature forest); 140 plots were examined including 2,789 trees. These plots included measurements of diameter at breast height (dbh). Using the allometric regression formulae of Jenkins et al. (2003; Table 2.2) dbh was converted to biomass and subsequently to biomass carbon density (t C/ha). Using the equations produces per tree biomass values in kilograms. Dividing by 2,000 gives the value in metric tons of carbon (throughout this report carbon is assumed to equal biomass x 0.5). To calculate landscape scale values expansion factors must be used. The Blodgett team measures trees > 4.5" dbh in 1/10 acre plots and trees < 4.5" dbh in 1/100 acre plots. Therefore to convert to t C/ha values, tree mass is multiplied by 24.71 for trees > 4.5" dbh and by 247.1 for trees < 4.5" dbh (1 hectare = 2.471 acres).

Table 2.2. The allometric regression equations of Jenkins et al. (2003) and the Blodgett Forest species to which they are applied

	Equation group	*Representative species*	*Regression equation*	*R^2*
Softwood	Cedar/larch	Incense cedar, Giant sequoia	Biomass (kg) = exp(-2.0336 + 2.2592 ln.*dbh)*	0.98
	Douglas-fir	Douglas fir	Bm (kg) = exp(-2.2304 + 2.4435 ln.*dbh)*	0.99
	True fir/hemlock	White fir, Pacific yew, Nutmeg	Bm (kg) = exp(-2.5384 + 2.4814 ln.*dbh)*	0.99
	Pine	Ponderosa pine, Sugar pine, Lodgepole pine	Bm (kg) = exp(-2.5356 + 2.4349 ln.*dbh)*	0.99
Hardwood	Mixed Hardwood	Chinquapin, Dogwood, Tanoak, Madrone	Bm (kg) = exp(-2.4800 + 2.4835 ln.*dbh)*	0.98
	Aspen / alder / cottonwood / willow	Alder spp.	Bm (kg) = exp(-2.2094 + 2.3867 ln.*dbh)*	0.95
	Hard maple / oak / hickory / beech	Black oak, Live oak, Maple spp.	Bm (kg) = exp(-2.0127 + 2.4342 ln.*dbh)*	0.99

2.2.1.2. Belowground biomass

Belowground biomass carbon can be added using the formula of Cairns et al. (1997), which is able to predict root biomass regardless of latitude, climate and edaphic conditions:

Root Biomass Density (t/ha) = exp[-1.085 + 0.925 ln(aboveground biomass density)]

$r^2 = 0.83$

2.2.1.3. Litter and duff

The depth of litter and duff (dead organic matter on the surface of the mineral soil) are measured as part of the Blodgett forest permanent plot methods. The BFRS plots measure the depth of litter and duff separately. This division has little meaning for biomass estimation and so the two were combined for all measurements and analyses discussed here. In order to produce a correlation with biomass carbon, measurements were taken of depth and mass, and subsamples were collected to determine dry mass. A strong relationship (n = 31, $r^2 = 0.91$) was obtained between depth and biomass carbon (Figure 2.4):

Litter/duff biomass carbon (t C/ha) = 5.4887x + 3.7141

where x = depth of litter/duff in cm

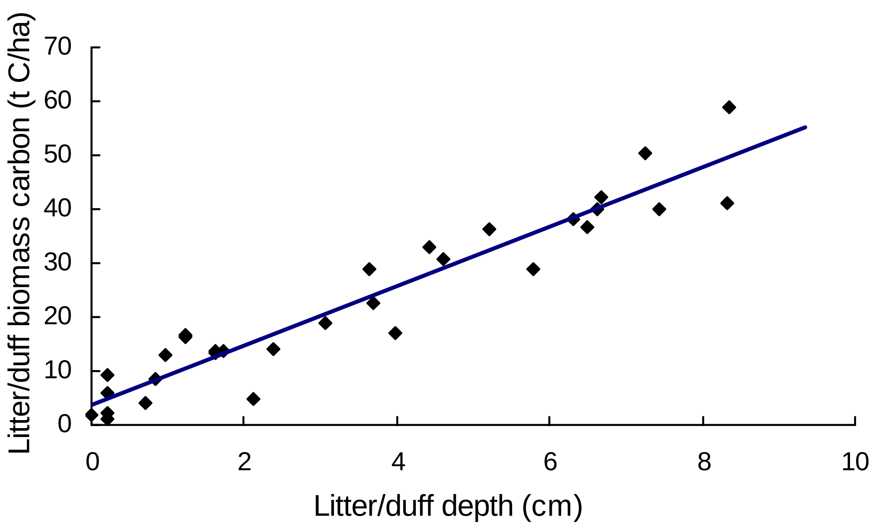


Figure 2.4. Relationship between litter/duff depth and biomass carbon

This relationship could then be applied to the BFRS permanent plot data to determine any relationships between forest age and litter biomass, or aboveground biomass and litter biomass.

2.2.1.4. Dead wood

Dead wood in the BFRS permanent plots is measured along two 37.2 feet lines. Dead wood with a diameter of > 3 inches is measured along the whole length of the lines, wood between 1 and 3 inches is measured along 10 feet and wood < 1 inch diameter is measured along 6 feet of each line. The line intersect method (Harmon and Sexton 1996) determines the volume of wood per hectare from the diameters of the pieces of wood that cross a line of a given length. We note that

Harmon recommends at least 100 m (about 328 feet) of line for this method to reduce the variability in this carbon pool (Winrock's standard method use two 50 m lines per plot).

$$\text{Volume } (m^3/ha) = \pi^2 * [(d1^2 + d2^2.......dn^2)/8L]$$

where d1, d2 etc = diameters of intersecting pieces of dead wood and L = length of the line. The volume is estimated for each density class separately.

The BFRS crews measure dead wood in five decomposition classes. Our experience has shown that five classes are too fine scale to have meaning with regard to biomass and so the five classes were combined into three coarser and consequently less ambiguous density classes: sound, intermediate and rotten.

Blodgett Class A	=	Sound
Blodgett Classes B and C	=	Intermediate
Blodgett Classes D and E	=	Rotten

In the BFRS plots no decomposition class is given to dead wood of < 3 inches and so here arbitrarily all dead wood of this size is given the intermediate class.

To determine biomass from calculated volume, the wood density at each decomposition stage (or density class) is required. We collected 26 samples across the three density classes. The estimated densities (Table 2.3) were used with the BFRS permanent plot data to create a relationship between forest age and lying dead wood biomass carbon.

Table 2.3. Oven-dried dead wood densities

Density Class	*Density (Mg/m^3)*	*95% Confidence Interval (CI)*
Sound	0.50	0.10
Intermediate	0.32	0.09
Rotten	0.17	0.06

Dead wood also can be found in the form of snags or standing dead wood. This also is measured in the Blodgett Forest permanent plots. The biomass of these trees can be calculated identical to the calculations for live trees with a subsequent deduction for the decomposition/degradation status of the tree. For the sake of simplifying calculations we arbitrarily use a limiting factor of 0.8 here to account for fallen needles, leaves, twigs and branches and in some cases tops.

2.2.1.5. Soil carbon

Soil samples were collected at seven sites to estimate the carbon content to 30 cm depth. The sites represent a recently logged forest—4 years after logging, 13 years after logging, and an old-growth site. After the litter and duff had been removed, a composite sample of three standard soil cores was collected for carbon measurements and one standard soil core for bulk density. The carbon content was measured by a commercial laboratory using the dry oxidation method.

Soil carbon is estimated as, in t C/ha: bulk density (g/cm^3) x depth (cm) x percent carbon (%). No corrections were needed for stones rock, fragments etc.

2.3. Modeling growth on the without project case: even-aged management

2.3.1. Aboveground live biomass

Blodgett forest was logged heavily early in the twentieth century and commercial clearcut logging was subsequently not restarted until volumes had recovered in the 1960s. As a consequence the forests in Blodgett are aged either between 70 and 100 years old or less than 40 years old, and there exists a missing section of data for any chronosequence calculations. This missing section was filled using a tree growth model. We used the Chapman-Richards growth model (Richards 1959; Pienaar and Turnbull 1973). The model was fitted as closely as possible to the Blodgett data to allow estimation of biomass for forests of any age (Figure 2.5). One compartment has no record of any harvest activity. Here arbitrarily the age of 200 years is given to this tract of forest to represent an age at which most facets of the forest should have reached maturity.

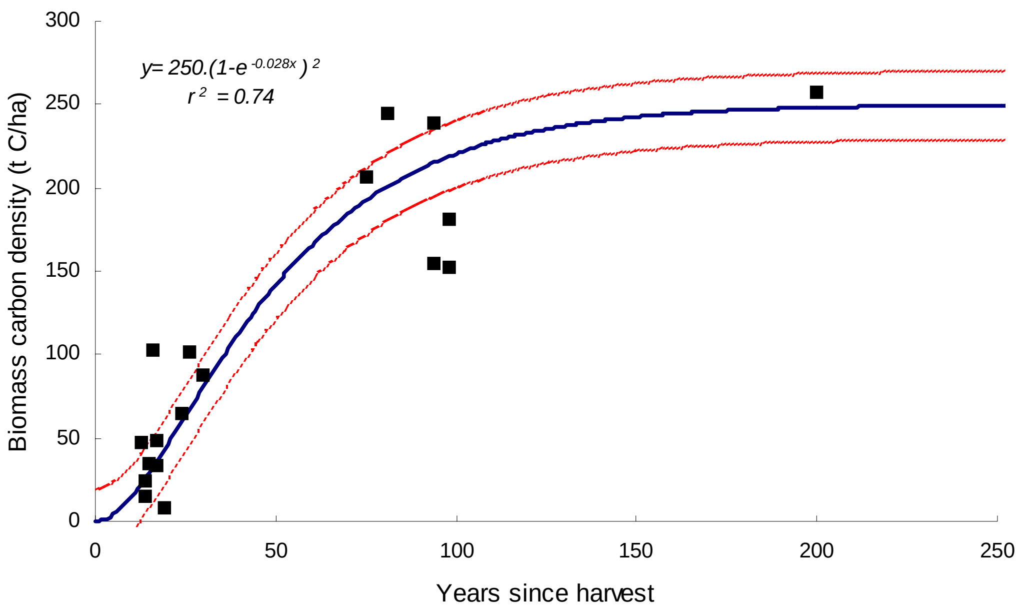


Figure 2.5. The Chapman-Richards curve fitted to the Blodgett plot data (± 95% Confidence Interval)

Model scenarios included the following assumptions: (1) all species considered together by defining average growth and tolerance among species, (2) absence of fire, and (3) no effect of reduced yields in successive harvests.

The 95% confidence intervals for estimated biomass carbon density were calculated as per Sokal and Rohlf (2003); referencing residual standard deviation between observed and predicted values.

In the absence of clearcut harvest and/or catastrophic disturbance, these even-aged stands are likely to become uneven-aged over time. At BFRS, stand re-initiation appears to start after approximately 100 years (R. York 2004, pers. comm.); this process will gradually lead to an uneven-aged condition.

2.3.2. Forest floor and dead wood

Biomass of litter and lying dead wood in the BFRS permanent plots were most closely related to compartment ages. In Figures 2.6 and 2.7, plot data for litter and dead wood respectively are plotted against compartment age. A regression curve was fitted to the data to allow a prediction of biomass carbon from age (Figures 2.6 and .7):

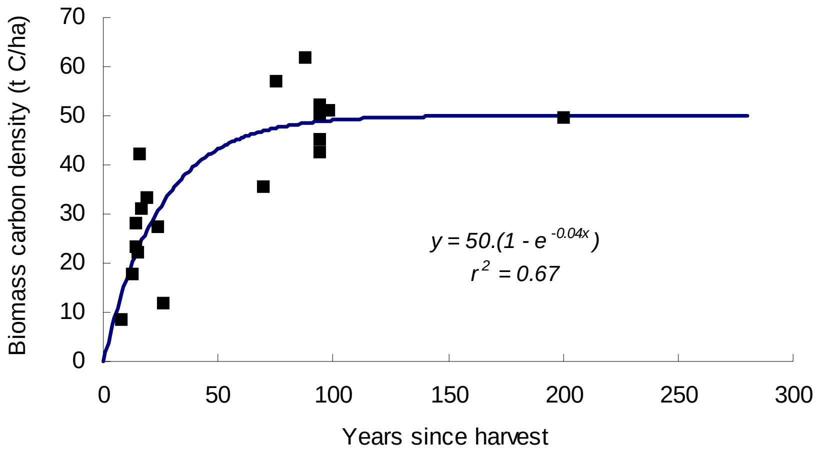


Figure 2.6. Relationship between forest age and biomass carbon of litter and duff

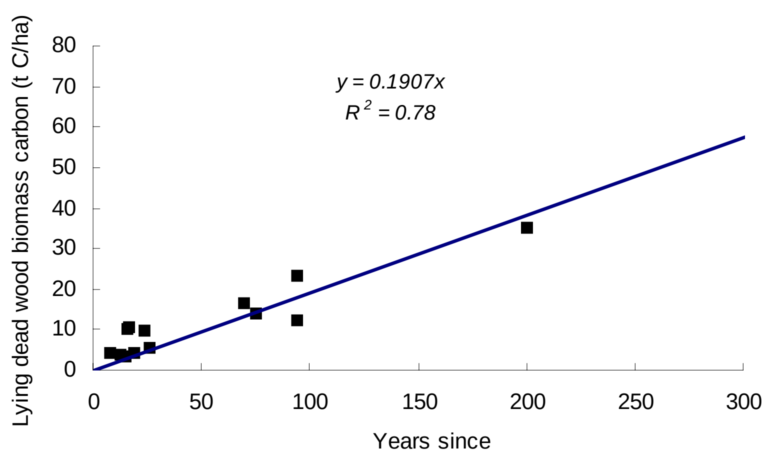


Figure 2.7. Relationship between forest age and biomass carbon of down dead wood

The litter layer can become a significant carbon pool especially under conifer species and in dry ecosystems such as exist at Blodgett. In the absence of fire, biomass accumulates steadily in this pool. Other authors have measured up to 100 t/ha in pinyon/juniper or 123 t/ha in ponderosa pine of a similar age to the older forests in this study (Tiedemann 1987; Covington and Sackett 1992). The value for ponderosa pine compares favorably with the maximum value of 124 t/ha calculated from the Blodgett dataset.

Standing dead wood correlated strongest with aboveground biomass. In Figure 2.8 the relationship between live aboveground biomass carbon density and the carbon density in standing dead trees is illustrated.

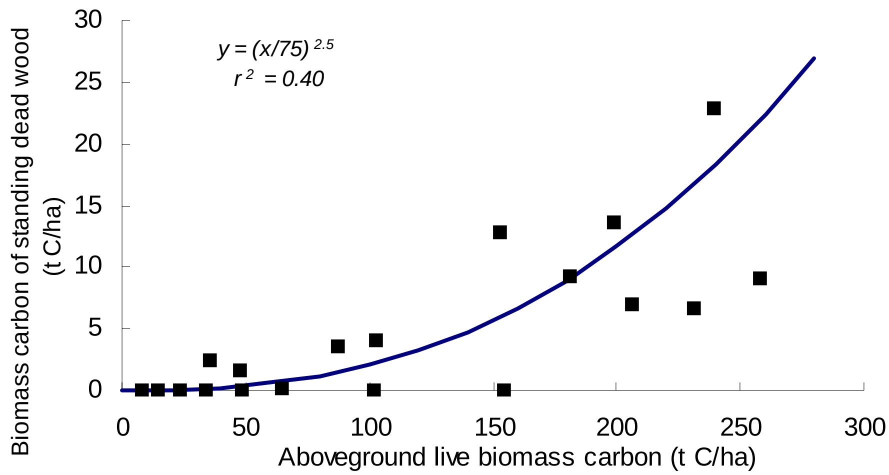


Figure 2.8. The relationship between aboveground live biomass carbon density and biomass carbon of standing dead wood

2.3.3. Soil organic carbon

The carbon content in the top 30 cm of soil ranged from 51 to 221 t C/ha across all sites. The mean carbon content of the old-growth site (78 t C/ha and 95% confidence interval [CI] of 13.9) was the lowest, followed by the 13-year-old site (mean 121 t C/ha, CI of 26), and the recently logged site (131 t C/ha, CI of 46.7). The soil measurements show a slight elevation in the amount of soil carbon in the 4-year-old compartments as compared to the old-growth compartments (analysis of variance with Tukey's test for pairwise comparison of means). The cause is probably the input of carbon matter following the slash-burning fires. However, the significance of this difference disappears within 10 years. Due to this short-term nature and relatively small extent of the effect, changes in soil carbon through time will not be considered in this analysis.

Differences in soil carbon resulting from changes in management are seldom discernible or long-lived. Soil carbon can be reduced slightly immediately following harvest (Laiho et al. 2002; Carter et al. 2002); however, any losses should be rapidly re-assimilated as the succeeding forest regrows with accompanying soil organic matter inputs (Carter et al. 2002). Relative difference in post-harvest effects on soil carbon between varying harvest intensities are slight and often undetectable (Carter et al. 2002). We thus assume that stocks of soil carbon are equal among the with- and with-out project cases and thus do not include this pool in the analysis.

2.3.4. Carbon pools summed

In Figure 2.9 the accumulation of biomass in each of the biomass components is modeled through 200 years. It should be noted that in the absence of fire, the dead wood pool continues accumulating biomass after all other pools have greatly diminished their accumulation rates. This is why many scientists consider stocks of dead wood as indicatory of the true maturity of a forest.

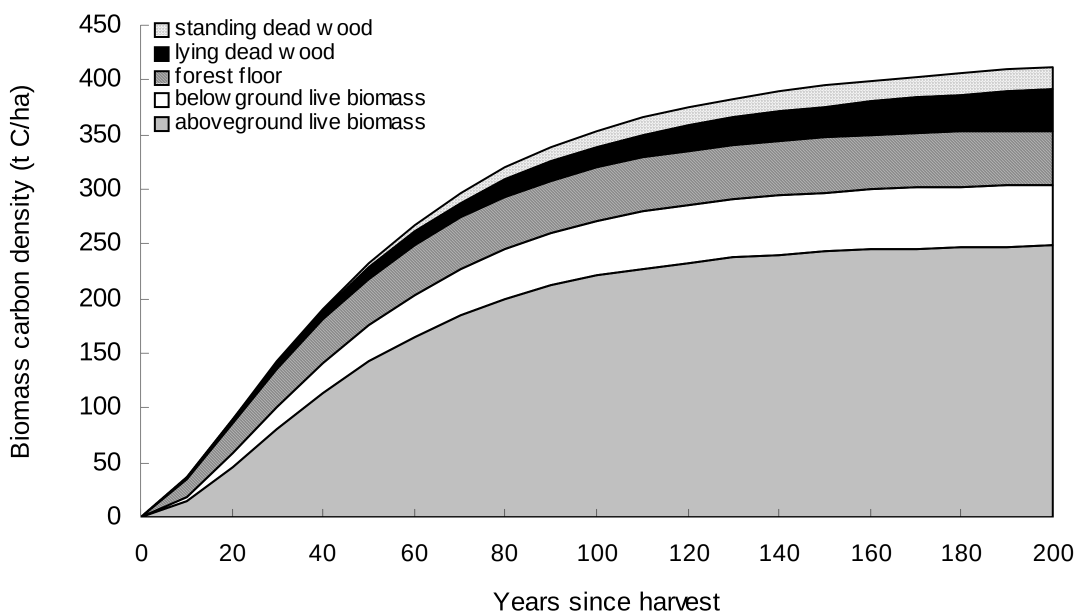


Figure 2.9. Carbon accumulation in a Californian Sierran forest modeled over 200 years

Following all the biomass-component additions it is possible to model the live vegetation over any growth cycle, including logging cycles typically applied to Sierran mixed conifers in California. In this region, even-aged management with an 80-year rotation is often applied in commercial forestry (Ed Murphy 2003, Sierra Pacific, pers. comm.), and once the timber has been extracted, litter, slash and any remaining vegetation is bulldozed into piles (Figure 2.10) and burned leaving virtually no residual biomass pools (personal observation). Modeling the forest cycle permits the long-term average biomass carbon density to be calculated (Figure 2.11). Here we estimate a long-term average over an 80-year rotation of 179.2 t C/ha (excluding derived long term wood products).

Figure 2.10. A slash pile in the forest at Blodgett

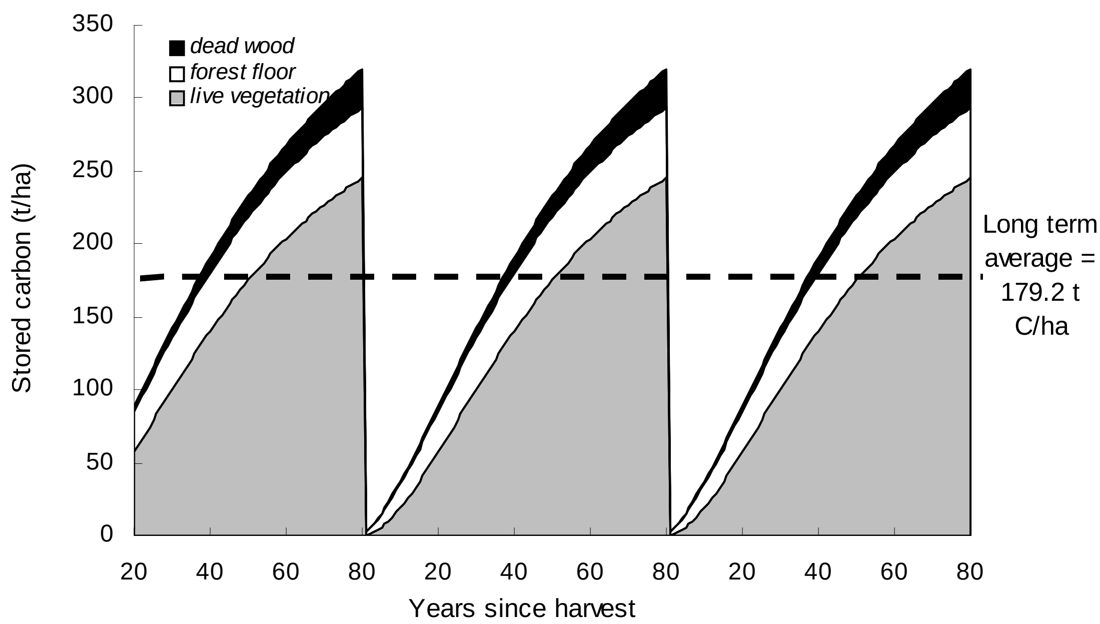


Figure 2.11. Growth and harvest cycles for live biomass in Sierran forests, the long term average biomass carbon density is indicated.

2.3.5. Long-term wood products

For any analysis of carbon benefits involving logging, long term wood products (LWPs) have to be considered. Timber felled in the forest is not immediately lost as emissions to the atmosphere. A proportion is carried to a processing mill; of this a proportion is converted into products, and, of this, a proportion of these products is destined for long term use (storage).

Each of these progressions has an efficiency associated with it, which was quantified and used to predict the fate of a typical removal of aboveground biomass via harvest. *Harvest efficiency* (i.e., biomass harvested as a percent of pre-harvest standing biomass) of 43% was used as reported by Birdsey (1996). Logging slash left on the site is assumed to be immediately oxidized as brush piles are burned shortly after harvest. Sawlog *transformation efficiency* conforms with conversion factors employed by Todd Morgan et al. (unpublished)—85% harvested stem wood = bole wood (15% bark), and 43% of bole wood converted to sawn wood and veneer (5.2 board feet per cubic foot). The resulting percentage of harvested volume, 37%, conforms closely with the same authors' independent findings based on year 2000 surveys of California mills, where 34% of wood fiber harvested was transformed to finished lumber or plywood/veneer. Relative production of all wood and waste products reported by Morgan et. al. included sizeable streams to cogeneration plants (34% of harvest) and pulp and paper (18% of harvest). For simplicity in this analysis, production streams are grouped into two classes: sawnwood and waste streams (Figure 2.12). As the only pulp mill in California sources from outside the Sierra Nevada region, pulp and paper streams were thus not considered in the model. "Waste streams," including wood fiber for cogeneration, landscaping material, and animal bedding, were defined based on anticipated short residence time of carbon and are assumed to be oxidized immediately in the model. The proportion of sawnwood products destined for long-term ($\geq$ 5 years) use were specified at 80% for sawnwood, based on findings summarized in Winjum et al. (1998).

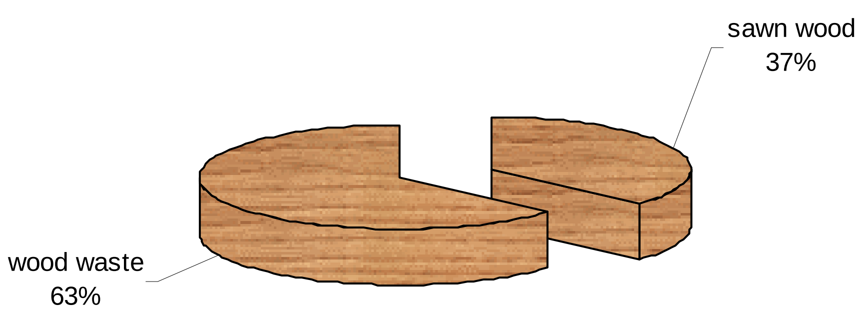
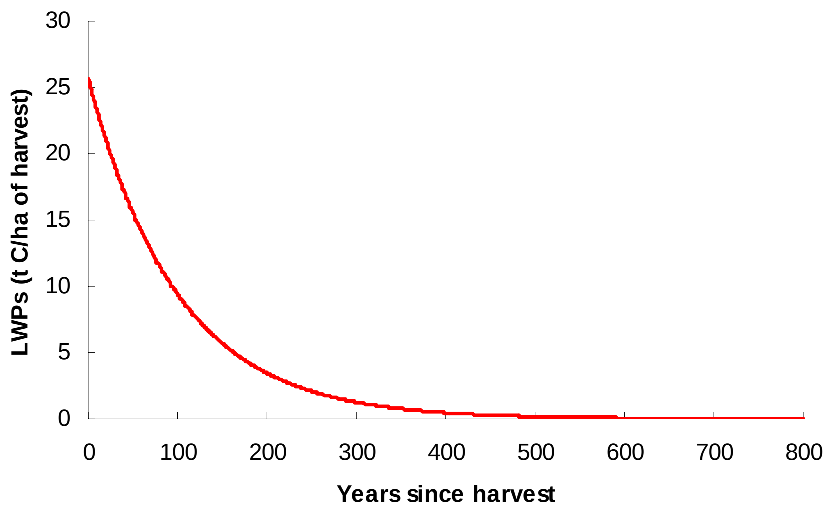


Figure 2.12. Proportions of harvested timber converted to saw and veneer logs and various wood waste streams as reported by Morgan et. al. (unpublished) from surveys of California wood product plants in 2000

Rates have been calculated for the oxidation of different LWPs through burning or decay. Wood products in long-term use are retired over time using an annual oxidation factor of 0.01 for sawnwood, as reported by Winjum et al. (1998). In Figure 2.13 the "retirement" (i.e., oxidation) of wood products from a mixed Sierran conifer forest is modeled both from a single harvest and from 80-year harvest cycles.

a.



b.

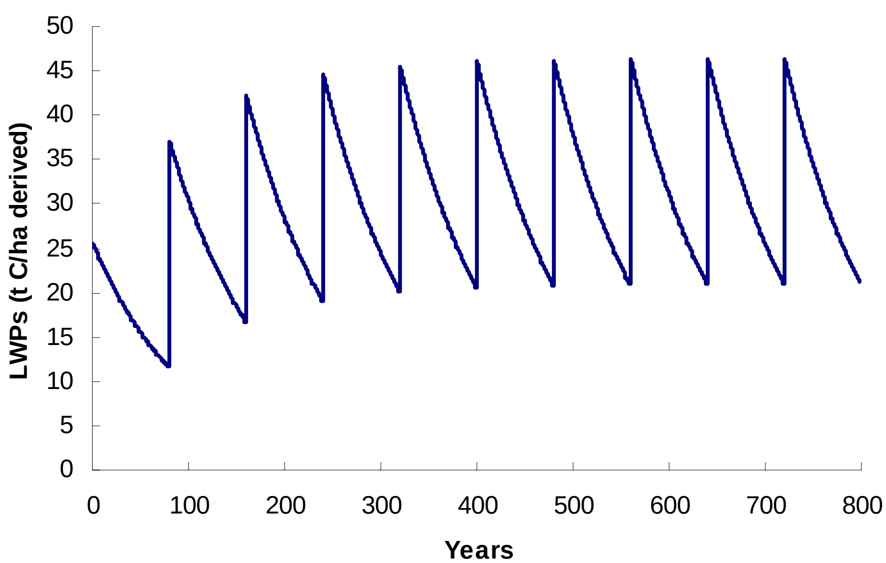


Figure 2.13. The oxidation of long-term wood products through time. (a) after a single harvest, and (b) with multiple harvests on an 80-year rotation

2.4. Change in the management of riparian buffers

2.4.1. With-buffer scenario

The with-buffer scenario envisages no management within the forested buffer area lying between 75 and 175 feet from the edge of one kilometer of modeled stream. The accumulation of carbon in live and dead vegetation is modeled through a 200-year period.

The starting condition is mixed Sierran conifer forest of four ages with separate examination of each initial forest condition. Forest ages are: 20 years old / 40 years old / 60 years old / 80 years old.

Three forest productivity classes, corresponding with low, medium, and high growth curves developed in Section 3.3.1, are examined.

2.4.2. Without-buffer scenario

In the without-buffer scenario, the forest in the 75- to 175-foot buffer area on each side of a modeled kilometer of stream is harvested on an 80-year rotation. At the time of harvest all slash is burned. The long-term average of carbon stored in live and dead vegetation and the net accumulation of carbon in long-term wood products is modeled through a 200-year period.

The starting condition is mixed Sierran conifer forest of four ages with separate examination of each initial forest age. Forest ages are: 20 years old / 40 years old / 60 years old / 80 years old.

Three forest productivity classes, corresponding with low, medium, and high growth curves developed in Section 3.3.1, are examined.

2.5. Results

Extension of the buffer zone and resultant protection of an additional 6.1 hectares per straight line kilometer of stream length results in a clear carbon storage benefit. Forest carbon continues to accumulate in the protected (with project) area, while forest carbon varies with successive harvests and regrowth in the managed (without project) area, resulting in a reduction in long-term average forest carbon storage (Figure 2.14). The reduction in long-term average forest carbon on the site subject to harvest is not offset by cumulative carbon storage in long-term wood products, even after hundreds of years of accumulation (Figure 2.15).

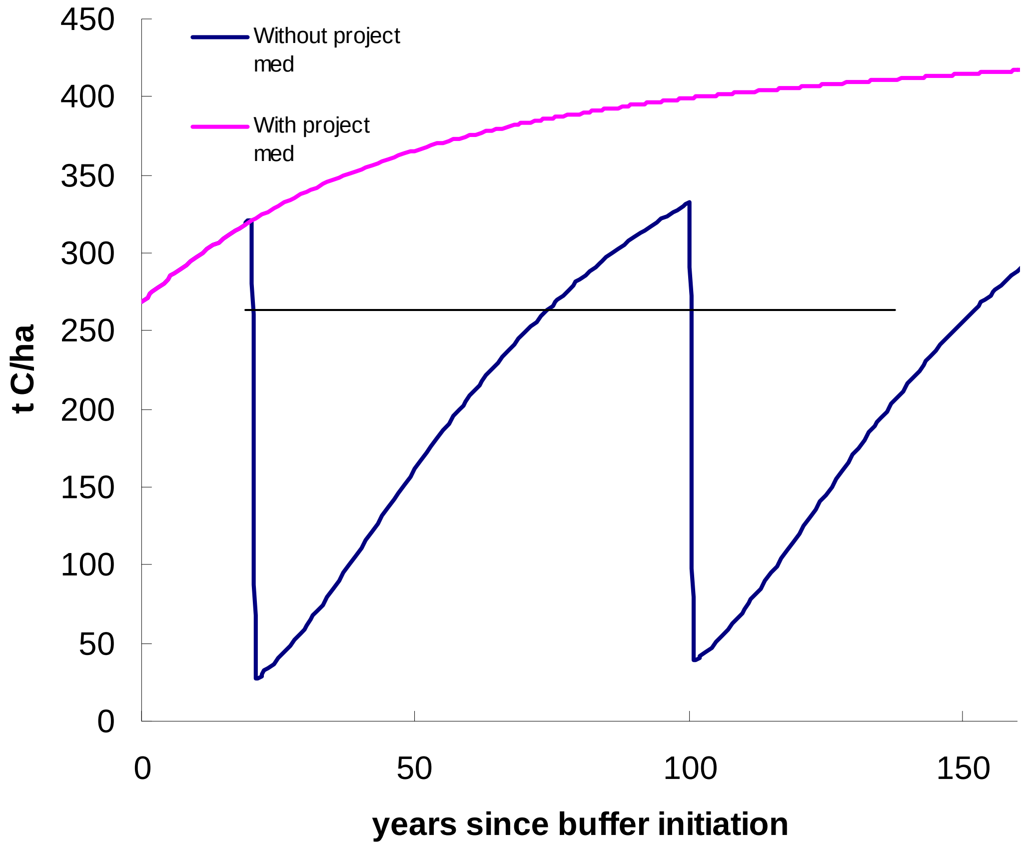


Figure 2.14. Comparative carbon accumulation in the extended buffer area with buffer (no harvest) and without buffer (even-aged management with an 80-year rotation) considering an initial stand age of 60 years on medium productivity site. Managed area (without protection) long-term (160-year) average carbon storage in all pools, including long-term wood products, is 199 t C/ha.

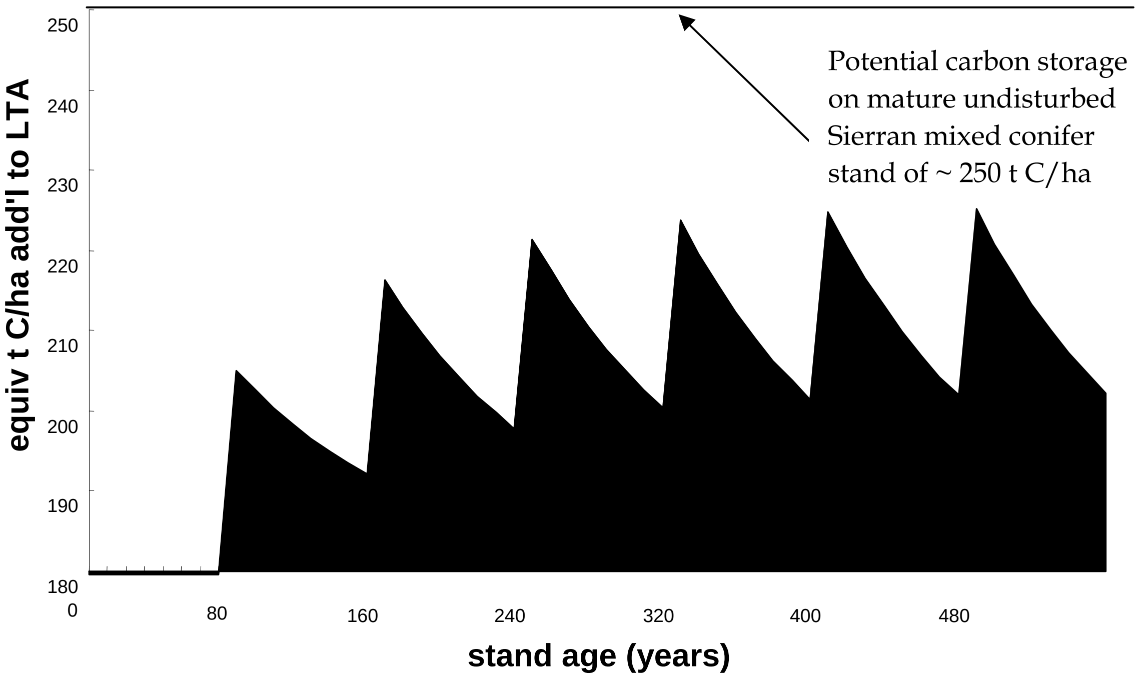


Figure 2.15. Accumulation of carbon in long-term wood products (LWPs) over and above the long-term average (LTA) *forest* carbon stock with management (180 t C/ha)

The calculation of long-term average carbon storage for the without-project case depends on the time scale considered but not substantially on initial forest age. The comparison was standardized among initial forest age scenarios (time scale used to derive long term averages was a multiple of rotation age) to ensure that all scenarios featured the same number of harvests and thus all scenarios were represented by various growth stages in the same proportions of the time under consideration. When standardized in this way, initial forest age is unimportant as a determinant of long-term average carbon storage which is consistently ~190 t C/ha (range = 185 to 197 t C/ha) for all initial forest age scenarios (for sites with 80-year rotation even-aged management and medium productivity) over an 80-year period (Figure 2.16). Long-term averages increase very slightly with older initial stand age due to the earlier harvest and consequently greater proportion of the period in which long term wood products are stored; and thus contribute to the average.

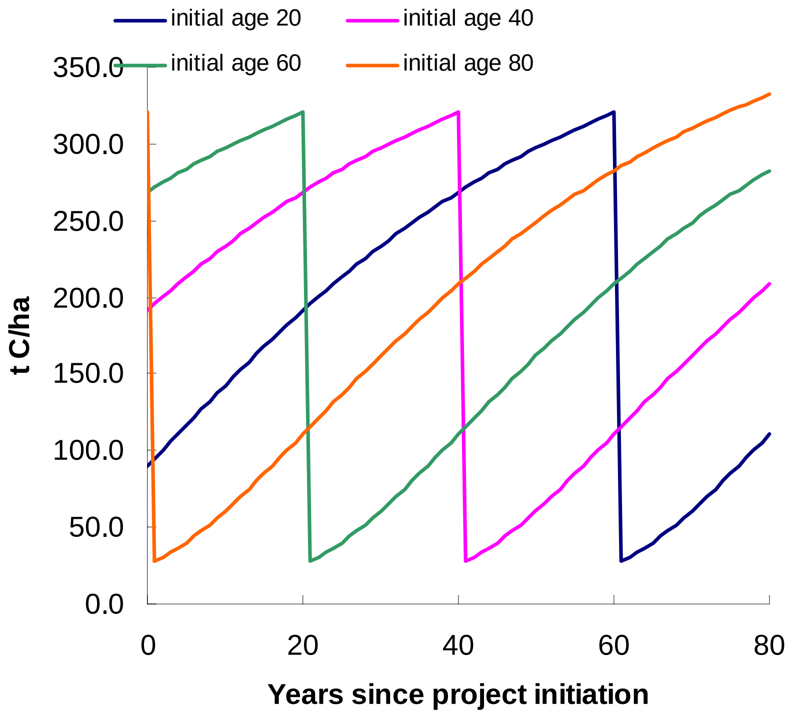


Figure 2.16. Carbon storage on 80-year rotation even-aged management and medium productivity with initial forest ages of 20, 40, 60, and 80 years

Relative differences between with-project carbon accumulation and without-project long-term average carbon stocks are similar among sites with different forest productivity. For example, estimated magnitude of carbon storage in the with-project case at 80 years *additional* to 80-year average carbon storage in the without-project case, with initial age 60, is roughly constant with 192 t C/ha (361 t C/ha with project – 169 t C/ha without project) for low productivity sites, 195 t C/ha (389 t C/ha with project – 194 t C/ha without project) for medium productivity sites, and 196 t C/ha (417 t C/ha with project – 221 t C/ha without project) for high productivity sites.

Thus, regardless of initial forest age and relative site productivity, carbon storage *benefits* of forest protection in the extended buffer zone are clear and consistently amount to ~ 1,100 - 1,200 tons of additional carbon per straight line kilometer of stream length after 80 years (190 t C/ha * 6.1 ha).

2.6. Carbon benefits

2.6.1. Riparian protection—extending the forested buffer

Extension of riparian buffer zones from 75 feet to 175 feet results in carbon storage *benefits* amounting to ~ 1,100–1,200 tons over the additional 6.1 hectares riparian forest retained per straight line kilometer of stream length after 80 years. The additional carbon results from continued accumulation of forest carbon in the protected (with project) area compared with varying forest carbon in the managed (without-project) area due to successive harvests and regrowth and consequent reduction in equivalent long-term average forest carbon storage. The reduction in forest carbon on the managed site is not offset by cumulative carbon storage in long-term wood products.

The estimates provided here are assessments of the potential carbon benefits from extending riparian buffer zones. In this report we have outlined details of the measurements and the types of analyses needed to calculate the with- and without-project carbon stocks when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring (see Appendix A). Where there are no existing inventory data additional measurements would be required but the analyses would essentially be the same as those given here. In a separate report we will provide more details on the methodology for collecting the field data.

2.7. References

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3.0 Jackson State Demonstration Forest

3.1. Background information

Jackson Demonstration State Forest (JDSF) is located inland of Fort Bragg in Mendocino County, California. The JDSF comprises more than 50,000 acres of predominantly coastal redwood or coastal redwood/Douglas fir forest. The land was acquired from the Mendocino Lumber Company and the Caspar Lumber Company between 1935 and 1951.

Between 1862 and the 1930s virtually all the virgin old growth comprising the coastal watersheds was cut (see Figure 3.1.). The forest now consists of second growth forest aged up to 140 years including very young stands that have been harvested while under state management.

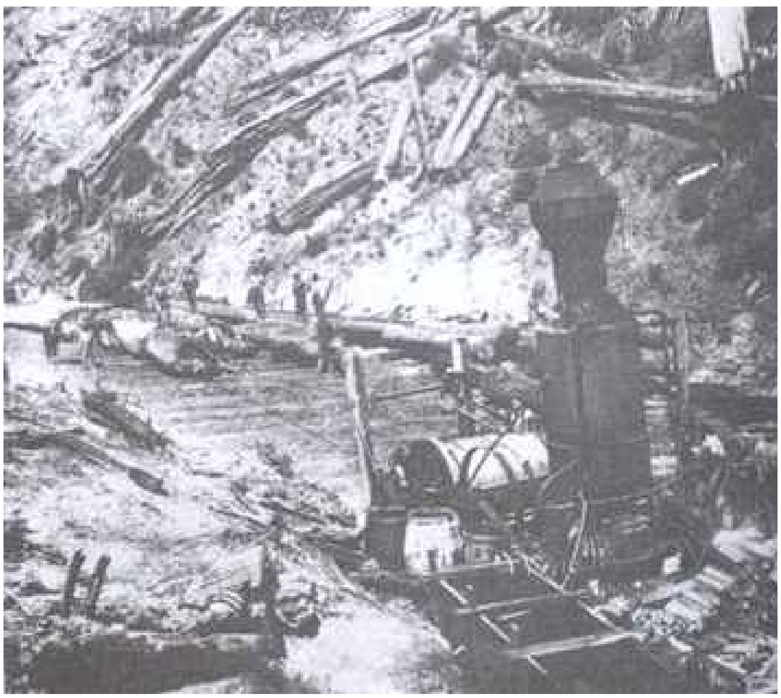

Figure 3.1. Engine and skid road circa 1890, Fort Bragg, California (from Williams 1989)

The JDSF was established as a demonstration of economical forest management. Its purpose has diversified more recently to include preservation of biodiversity and the fostering of mature forest structure as well as remaining a "viable and relevant laboratory for resource professionals, private timberland owners, and the general public" (CDF 2002).

We visited JDSF in February 2004 to collect data required for biomass estimations. Some of the sites visited are illustrated in Figure 3.2. Measurements were made of trees in and around clearcuts (e.g., Figure 3.3) and group selections and of dead wood, litter, understory and soil carbon. Other data were obtained from JDSF the measurements of permanent plot made by staff at JDSF.

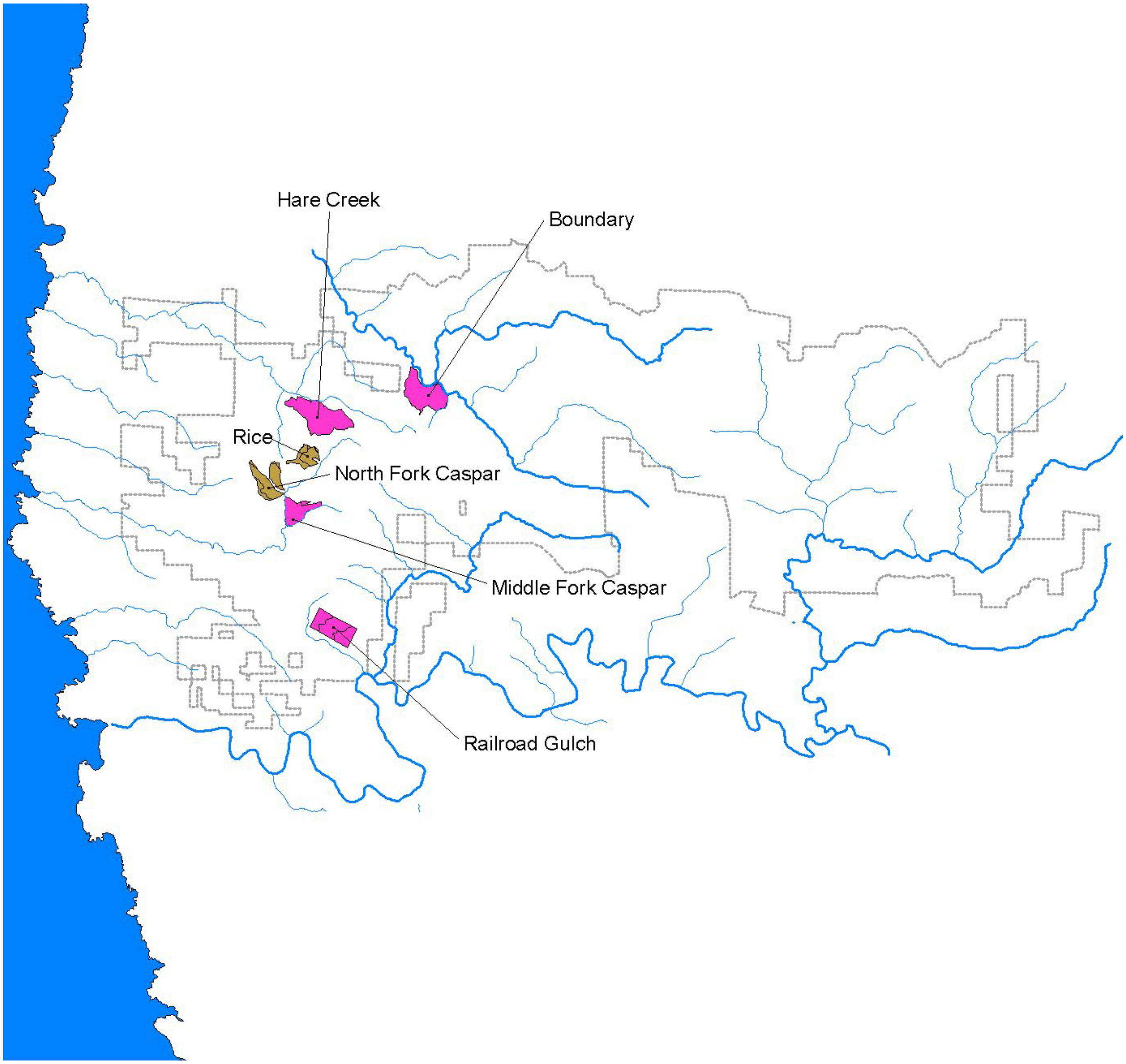

Figure 3.2. Jackson Demonstration State Forest. The location of field investigation sites is indicated.

The tree species commonly encountered at Jackson are listed in Table 3.1.

Table 3.1. The tree species of JSDF. Dominant species are in bold. Commercially grown species are underlined.

Hardwoods	Conifers
Tan Oak	**Coastal Redwood**
Pacific Madrone	**Douglas-Fir**
Red Alder	Grand Fir
California Bay	Western Hemlock
Canyon Live Oak	Bishop Pine
Willow	Cypress
Bigleaf Maple	
Eucalyptus	

Figure 3.3. Fifteen-year-old stand of redwood regenerating after a clearcut at JDSF

3.2. Accumulation of carbon on growing redwood stands

Mature redwood stands are famous for their enormous stocks of standing biomass and represent perhaps the most massive forests, per unit area, on earth. Measurements of old-growth (> 200 years) redwood stands have yielded standing carbon stocks ranging from 1,650 to 1,784 t C equivalent per ha (Hallin 1934; Westman and Whittaker 1975; and Fujimori 1977). Equally impressive is the rate at which carbon is sequestered in growing redwood stands. A 100-year-old redwood stand measured by Olson et al. (1990) yielded 3,600 cubic meters per ha, equivalent to 648 t C per ha (at specific gravity 0.36 g oven-dry biomass/cm^3 for second-growth redwood (Markwardt and Wilson 1935)), or a mean annual carbon increment of 6.48 t C per ha per year.

3.3. Biomass calculations for Jackson forest

3.3.1. Aboveground live biomass

The calculations of aboveground live tree biomass presented here are based on the empirical yield tables of Lindquist and Palley (1963). Although 40 years old, these tables represent redwood growth in the region well (Marc Jameson 2004, Forest Manager JDSF, pers. comm.). Here the mean dbh (diameter at breast height) and number of trees per acre over 4.5" dbh is used to calculate a biomass carbon density at ages between 20 and 100 years. The dbh is converted to tree biomass using the appropriate formula of Jenkins et al. (2003; Table 3.2). Kilogram biomass values are converted to tons of carbon by dividing by 2000 (mass of carbon = 50% dry biomass).

Table 3.2. The allometric regression equations of Jenkins et al. (2003) and the Jackson Forest species to which they are applied

	Equation group	*Representative species*	*Regression equation*	R^2
Softwood	Cedar/larch	Coastal Redwood, Cypress spp.	Biomass (kg) = exp(-2.0336 + 2.2592 ln.*dbh*	0.98
	Douglas-fir	Douglas fir	Bm (kg) = exp(-2.2304 + 2.4435 ln.*dbh*	0.99
	True fir/hemlock	Grand Fir, Western Hemlock	Bm (kg) = exp(-2.5384 + 2.4814 ln.*dbh*	0.99
	Pine	Bishop Pine	Bm (kg) = exp(-2.5356 + 2.4349 ln.*dbh*	0.99
Hardwood	Mixed Hardwood	Tanoak, Pacific Madrone, Eucalyptus, California Bay	Bm (kg) = exp(-2.4800 + 2.4835 ln.*dbh*	0.98
	Aspen / alder / cottonwood / willow	Alder spp., Willow spp.	Bm (kg) = exp(-2.2094 + 2.3867 ln.*dbh*	0.95
	Hard maple / oak / hickory / beech	Canyon Live oak, Maple spp.	Bm (kg) = exp(-2.0127 + 2.4342 ln.*dbh*	0.99

The site index of 160 was chosen as the representative class with 180 and 120 as the upper and lower bounds respectively (CDF 2002; Shih 2002; Marc Jameson 2004, Forest Manager JDSF, pers. comm.).

The biomass yield curves were extrapolated beyond 100 years using first order approximations. The extrapolation was based on plotting an exponential regression curve through the decreasing annualized increase in biomass predicted from the yield tables. In this way the increase in biomass in year 101, 102, 103, etc. could be predicted and added to the total to create a biomass carbon density curve over 250 years (Figure 3.4).

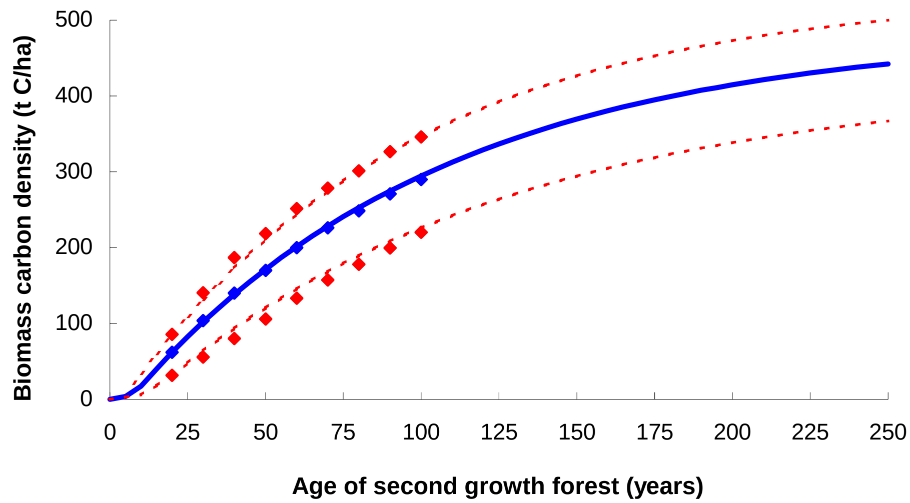

Figure 3.4. Growth curves for redwoods at site indices of 120, 160, and 180. The points represent the results from the yield tables (Lindquist and Pelley 1963), the curves are extrapolation of these points.

Ideally to provide additional verification for the growth curves, forest inventory data would be examined. The CDF installed continuous forest inventory (CFI) plots across Jackson forest in the 1960s and these have been measured at least every 10 years. In these plots, amongst other information, dbh (for trees > 7" dbh), is measured.

There are 141 CFI plots and they were last measured in 1999. Between 1988 and 1989 a further 1,506 intensive forest inventory (IFI) plots were installed. However this only totals 1,647 plots over 50,000 acres. Consequently any analysis of these plots produces very wide degrees of variability reflecting the wide range of forestry practices, species compositions, edaphic factors and topography represented at Jackson.

An additional problem is caused by the need to accurately locate the plots. Neither the location of the forestry units nor the locations of the inventory plots were ever identified by global positioning systems. The result is a frequent mismatch between the forest history and the inventory data. To deal with this problem only plots that were located more than 50 m inside forestry units were included.

The number of plots available for analysis that were in even-aged stands and were more than 50 m inside units only totaled 388. This limited number of plots and the wide degree of variable conditions represented by these plots resulted in data has limited use for estimating carbon stocks with any degree of precision. Consequently here the stand tables are relied upon as the sole source of aboveground tree biomass information.

3.3.2. Belowground biomass

Belowground biomass carbon can be added using the formula of Cairns et al. (1997), which is able to predict root biomass regardless of latitude, climate and edaphic conditions:

Root Biomass Density (t/ha) = exp[-1.085 + 0.925 ln(aboveground biomass density)] $r^2 = 0.83$

In the case of JDSF, this should be viewed as an underestimation given that new redwood sprouts grow on the root stock of the harvested trees.

3.3.3. Litter and duff

During our visit to JDSF in February 2004, litter stocks were measured at 5 stands (n=28) ranging in age from 14 to ~130 years. Analysis of the measurements derived a model (R^2 = 0.66) to describe the accumulation of biomass carbon stocks in litter (Figure 3.5). The form of the model is:

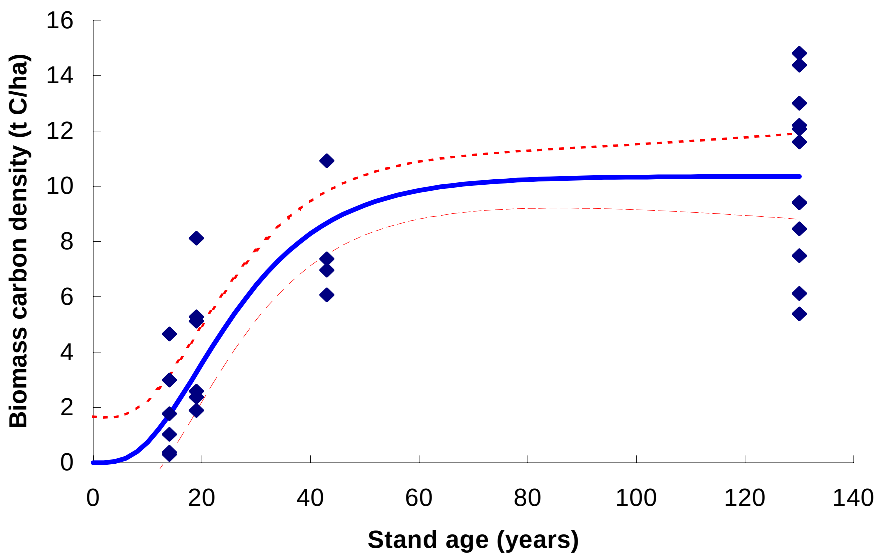

Figure 3.5. Inferred accumulation of biomass carbon in litter on aggrading redwood stands at JDSF with 95% confidence intervals. Biomass carbon density of litter (t C/ha) = 10.4 * (1 - exp(-0.073 * forest age))^4 .

Litter in older (~130 years) stands averaged 10.4 t C/ha. Pillars and Stuart (1993) demonstrated that mean annual litterfall in mature redwood stands averaged between 1.6 to 2.4 t C equivalent per ha, which must be balanced by equal decomposition to result in the apparently stable stocks of litter noted in mature stands.

3.3.4. Dead wood

Redwood is known for its rot resistance and exhibits very low decomposition rates. Cut stumps and log sections dating from harvest operations conducted over 100 years previous were readily apparent throughout JDSF (Figure 3.6).

Studies of downed woody debris in old-growth coastal redwood stands of Mendocino and Humboldt Counties have yielded carbon stocks in downed woody debris ranging from 13 to 100 t per ha (Bingham and Sawyer 1988; Bingham 1992).

Figure 3.6. Remnant log section from a cut dating from circa 1860–1890

In JDSF, as part of the continuous forest inventory (CFI) process, down dead wood is measured in 141 plots at least every ten years. Logs larger than 7″ diameter on the large end are measured in a 26.3′ radius plot and logs larger than 11″ on the large end are measured in a 52.7′ radius plot. Logs are only measured where at least one-half of the log lies within the plot boundary. Due to the necessity to select even-aged compartments and the problems discussed in Section 3.1 with identifying the history of the plots, only 29 plots could be examined across 9 different ages. These plots are spread over 50,000 acres and so the spacing is wide, encompassing a wide range of topography, edaphic conditions and species groupings. Consequently wide variation can be expected in what is already an inherently highly variable forest carbon pool (discrete patches of dead trees, created by disturbance, are a defining element in the distribution of dead wood across a landscape).

The down dead wood is classified in one of five decomposition classes (c.f. Maser et al. 1979). Our experience has shown that five classes are too fine scale to have meaning with regard to biomass and so the five classes were combined into three coarser and consequently less ambiguous decomposition classes: sound, intermediate, and rotten.

Jackson Class 1	=	Sound
Jackson Classes 2 and 3	=	Intermediate
Jackson Classes 4 and 5	=	Rotten

To determine biomass from calculated volume, the wood density at each decomposition stage is required. We collected 30 samples across the three density (or decomposition) classes. The densities (Table 3.3) were used with the JDSF permanent plot data to create a relationship between forest age and lying dead wood biomass carbon. It is worth noting the close correspondence of the sound density measured here, 0.34 Mg/m^3, with known density of redwood, 0.36 Mg/m^3 (Markwardt and Wilson 1935), testament to the dominance of redwood in this forest community.

Table 3.3. Oven dried densities of decomposed dead wood

Density Class	*Density (Mg/m^3)*	*95% CI*
Sound	0.34	0.05
Intermediate	0.25	0.03
Rotten	0.16	0.03

The biomass carbon density of the eligible CFI plots is plotted, averaged across the nine age classes (Figure 3.7). A regression curve was fitted with an r^2 of 0.79. The wide spread in the data can be expected from the limited number of plots representing a diverse topography with additional variation arising from a range of site indices (edaphic conditions) and a range of species groupings. However, the predicted biomass carbon density of 17 t C per hectare at 250 years is within the range of old growth down dead wood values of between 13 and 100 t C per hectare (Bingham and Sawyer 1988; Bingham 1992). The highest quantities of dead wood would in fact be expected in old-growth redwood stands as only in very mature stands will very large trees die, fall and begin to decompose slowly on the forest floor.

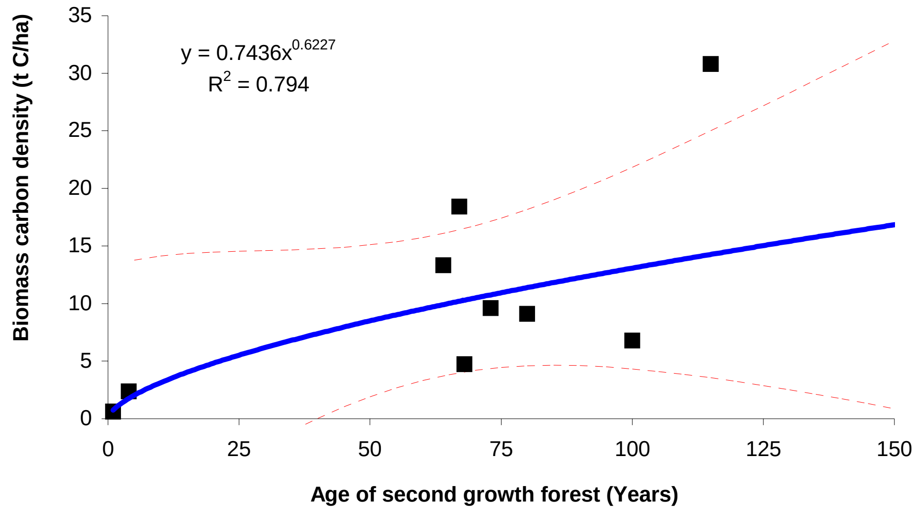

Figure 3.7. Relationship between biomass carbon accumulation in down dead wood and forest age +/- 95% confidence intervals

Dead wood also can be found in the form of snags or standing dead wood. Although this is also measured in the JSDF CFI plots, it is not considered in the model as a dynamic pool given the difficulty of discerning any accumulation trend (dead wood in forests typically has a short residence time as *standing* dead wood (Franklin et al. 1996), as well as the fact that snags are often retained on site to provide wildlife habitat after harvest (thus stands at age zero may have significant standing dead wood stocks).

3.3.5. Understory vegetation

Understory vegetation in the mature stands was mostly dominated by ferns (Figure 3.6). Carbon in understory vegetation samples did not differ appreciably among young (14-19 years) and old (114-144 years) redwood stands. The estimated mean across all of these ages (n=28) was 0.4 t C/ha and was highly variable from site to site (95% CI = +/- 0.4 t C/ha). As understory is constant across age classes and represents very little biomass, it will not be included in calculations in this study.

3.3.6. Soil organic carbon

Thirty soil samples were collected from four sites at JDSF. Each of the samples included measurements of soil carbon and bulk density. The four sites were comprised of two pairs of adjacent young and older growth. No significant differences were noted between the adjacent recently cut (i.e., within the past 14-19 years) and older growth (> 114 years) redwood stands (Figure 3.8).

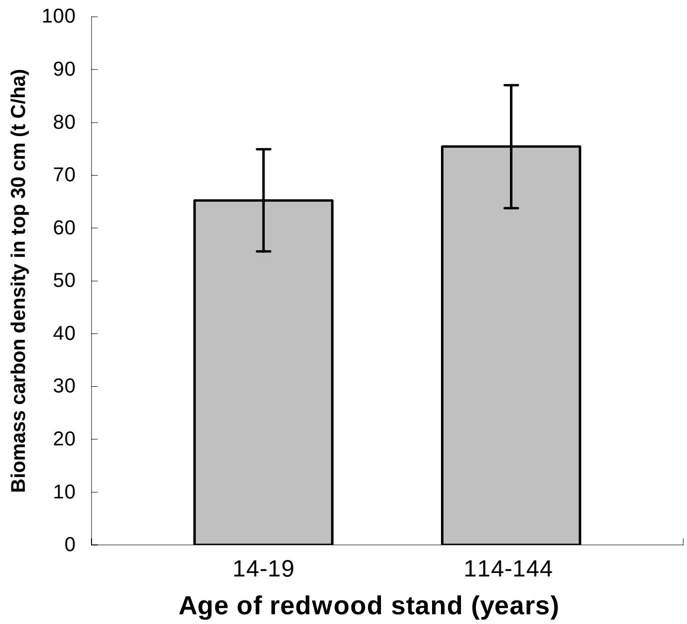

Figure 3.8. Comparative soil carbon in redwood stands harvested 1985/1990 (n=14) and circa 1860–1890 (n=16) at JDSF. Error bars equal 95% confidence interval. Differences are not significant.

Differences in soil carbon resulting from changes in management are seldom discernible or long-lived. Soil carbon can be reduced slightly immediately following harvest (Laiho et al. 2002; Carter et al. 2002), however, any losses should be rapidly re-assimilated as the succeeding forest regrows with accompanying soil organic matter inputs (Carter et al. 2002).

Relative difference in post-harvest effects on soil carbon between varying harvest intensities are slight and often undetectable (Carter et al. 2002). We thus assume that stocks of soil carbon are equal among the with- and with-out project cases and thus do not include this pool in the analysis.

3.3.7. Harvest efficiency, slash and long-term wood products

For any analysis of carbon benefits involving logging, slash and long term wood products (LWPs) must be added. Timber felled in the forest is not immediately lost as emissions to the atmosphere. A proportion is left on site to decompose as slash and a proportion is carried to a processing mill; of this second proportion a further proportion is converted into products, and of this a proportion of these products is destined for long term use (storage).

Harvest efficiency (i.e., biomass harvested as a percent of pre-harvest standing biomass) was determined as the percent stem volume to a 6-inch diameter inside the bark, following standard commercial limits, using the stem taper function and bark ratio and taper functions derived by Krumland and Wensel (1978). Volumes were determined for ≤ 20 foot log sections of a 90-year old, rotation age, redwood stem of mean dimensions for site index 160 (24.1 inches dbh and 152 feet total height) using Smalian's formula, and volume of the top section was calculated assuming the shape of a paraboloid cone. The top (remaining) section, equal to 1%

aboveground stem volume (diameter inside bark equals 6 inches at 129 feet total height), is left on the site as logging slash. We thus assume that 99% (100%–1% top section) of aboveground stem volume (> 1 foot height) is extracted in a typical harvest operation. As dry mass per unit volume is constant, allocations of volume among components are equally reflective of allocations of mass.

Branch and stem (wood and bark) components, as a percentage of total aboveground biomass, were estimated at 16% and 79%, respectively, as per biomass component ratios developed by Jenkins et al. (2003), referencing the mean 90-year-old redwood stem described above. Harvest efficiency is thus 78% of aboveground biomass (79% stem * 99% merchantable portion). Slash or woody debris remaining thus equals 17% of aboveground biomass (16% branches + (1% top section * 79% stem)).[1] Much of harvest slash is smaller than the 7" minimum diameter recorded for down dead wood in CFI plots (Figure 3.9), and thus is unaccounted for in the accumulation curve for down, and coarse, dead wood. Decomposition of slash is modeled at a rate of 0.05 yr^{-1} (Harmon et al. 1987).

Figure 3.9. Logging slash on a 15-year-old group selection at the Boundary stand, JDSF

The transformation efficiency of receiving mills (e.g., relative output sawtimber, chips, bark, sawdust) was substantiated via interviews with local operators including Mendocino Redwood Company, Simpson Timber Company, Pacific Lumber Company, Willits Redwood Company, and Redwood Empire (Figure 2.10). Reported production quantities were standardized to dry metric tons, assuming specific gravity (dry mass/green volume) = 0.36 g/cm^3, dry weight =

1 The remaining ~5% of aboveground biomass is foliage, oxidized immediately in the model.

50% green weight, chips and bark reported volumes (i.e., cubic yards) assume 25% airspace, and sawdust reported volumes assume 5% airspace.

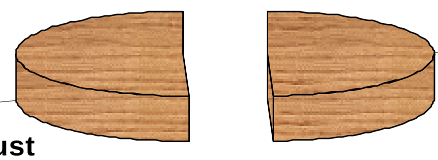

Figure 3.10. Mean proportions of harvested redwood saw logs converted to boards and "waste" streams derived from interviews with northern California sawmill operators (n = 5)

Most of the sawn timber is destined for local/domestic consumption, primarily for use in decking, fencing, and other outdoor lumber products. Chips, which represent 20% to 29% of product streams, are sold as landscaping material, and to a smaller degree are used in cogeneration and paper pulp production. With only a single pulp mill operating in the region (and statewide), a very small portion of chips are captured by the pulp market. Pulp and paper streams were thus deemed insignificant at the region level and are ignored in the model. Bark, representing 16% to 23% of saw log output, is used for landscaping material and as "hog fuel" in cogeneration. Sawdust and shavings, making up 7% to 24% of output, are likewise used primarily for landscaping, and to a lesser extent in fiber board production. Given the anticipated short residence time of carbon in chips, bark, and sawdust used as landscaping material, their primary end use, these pools, like biomass used in cogeneration, are assumed to be oxidized immediately in the model. The proportion of sawn wood products destined for long-term ($\geq$ 5 years) use were specified at 80% for sawn wood, based on findings summarized in Winjum et al. (1998).

Rates have been calculated for the oxidation of different LWPs through burning or decay. Wood products in long-term use were "retired" (i.e., oxidized) over time using an annual oxidation factor of 0.01 for sawn wood products, as reported by Winjum et al. (1998).

3.3.8. Carbon pools summed

The accumulation of biomass carbon over 250 years is modeled for each of the significant biomass carbon pools (Figure 3.11). At these ages above- and belowground biomass dominates. Forest floor is much less significant than in Blodgett where needles accumulate and in the dry conditions fail to decompose rapidly. Down dead wood remains a relatively small component even at 250 years of age but it is expected that accumulation would continue for many years after the other pools have stabilized. The biggest addition of dead wood will occur when the mature trees die and fall to the forest floor; for redwoods that live for thousands of years these great additions of down dead wood might not occur until 500 years or more have passed. For example, log volumes recorded in stream channels through old growth redwood yielded 2 to 11 times the mass per unit area as from streams through 100–130 year old second growth redwood stands on the north fork of Caspar creek (Napolitano 1998).

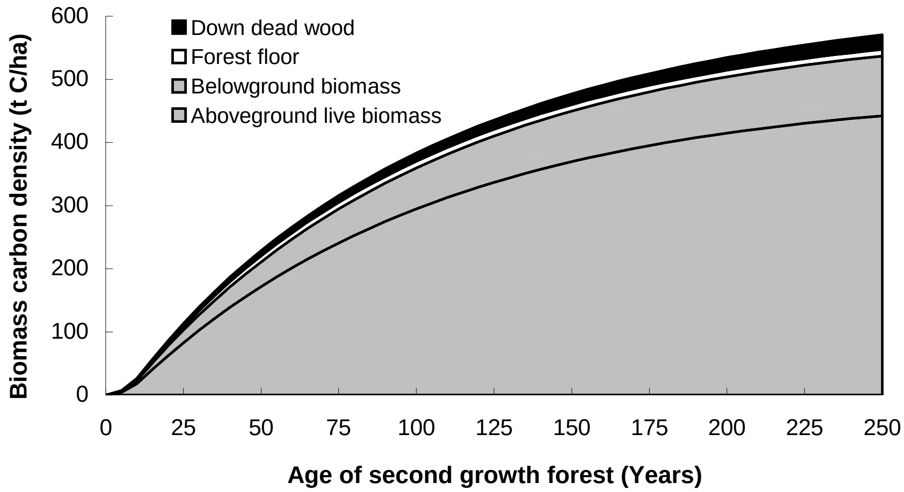

Figure 3.11. Sum of each of the significant biomass density pools for second-growth redwood forest accumulating over 250 years. A site index of 160 and the moderate levels for down dead wood and forest floor are illustrated.

In Figure 3.12 a typical redwood harvesting cycle is illustrated including logging slash and long-term wood products and the decomposition of both components. Both logging slash and long-term wood products accumulate through time as the time for complete decomposition exceeds the harvest cycle. However, if the scenarios were to be modeled far enough into the future, eventually a state would be reached where the decomposition from all slash and LWPs from all the past cycles is equal to the input of new slash and LWPs and no new accumulation would be seen.

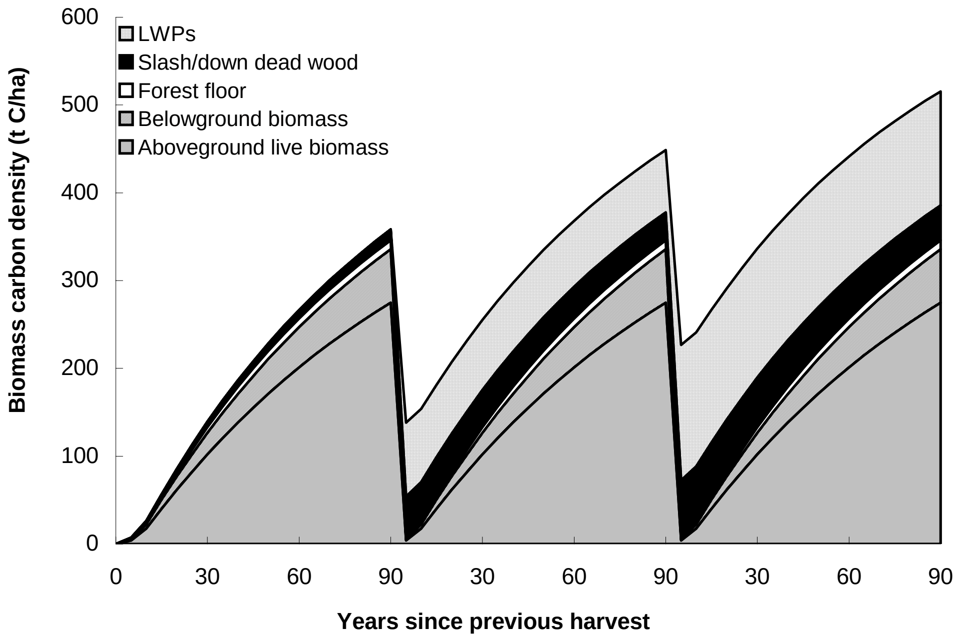

Figure 3.12. Sum of each of the significant biomass carbon pools in and derived from second-growth redwood forest accumulating over three harvest (clearcut) cycles. A site index of 160 with moderate levels for down dead wood and forest floor is illustrated.

Once these initial conditions have been established then biomass can be modeled over typical harvesting scenarios. A rotation age of 90 years will be used in this analysis, reflecting the mid point between short and long rotations (60 to 120 years) as prescribed in the Jackson Demonstration State Forest Management plan (California Department of Forestry and Fire Protection 2002), though mean annual increment may not peak until stands exceed 100 years (Noss 2000).

3.4. Change in the management of riparian buffers

3.4.1.1. With-buffer scenario

The with-buffer scenario envisages no management within the forested buffer area lying between 100 and 200 feet from the edge of one kilometer of modeled stream. The accumulation of carbon in live and dead vegetation is modeled over one rotation or 90 years.

The starting condition is coastal redwood forest of four ages with separate examination of each initial forest condition. Forest ages are: 30 years old / 60 years old / 90 years old.

Three forest productivity classes, corresponding with low (site index 120), medium (site index 160), and high (site index 180) growth curves developed in Section 3.3.1, are examined.

3.4.1.2. Without-buffer scenario

In the without-buffer scenario, the forest between 100 and 200 feet from the edge of one kilometer of modeled stream is harvested on an 90-year rotation. The long-term average of carbon stored in live and dead vegetation and the net accumulation of carbon in long-term wood products is modeled over one rotation or 90 years. The starting condition is coastal redwood forest of four ages with separate examination of each initial forest condition. Forest ages are: 30 years old / 60 years old / 90 years old. Three forest productivity classes are also modeled, corresponding with low (site index 120), medium (site index 160), and high (site index 180) growth curves developed in Section 3.3.1.

3.4.2. Results

Over one rotation, average carbon storage including harvest-derived pools of slash and long term wood products in the without project case (i.e., no extended buffer), 275 t C/ha, is easily exceeded by the steadily growing, unharvested stand (Figure 3.13). Results are consistent across site productivities and initial stand ages (Table 3.4). In the without project case, average carbon storages derived for equivalent periods increase with increasing initial stand age due to the earlier harvest and consequently greater proportion of the period in which long term wood products are stored; and thus contribute to the average. This "advantage" is however eclipsed by the increase in forest biomass accumulated at the end of the same period by unharvested forest of increasing initial age.

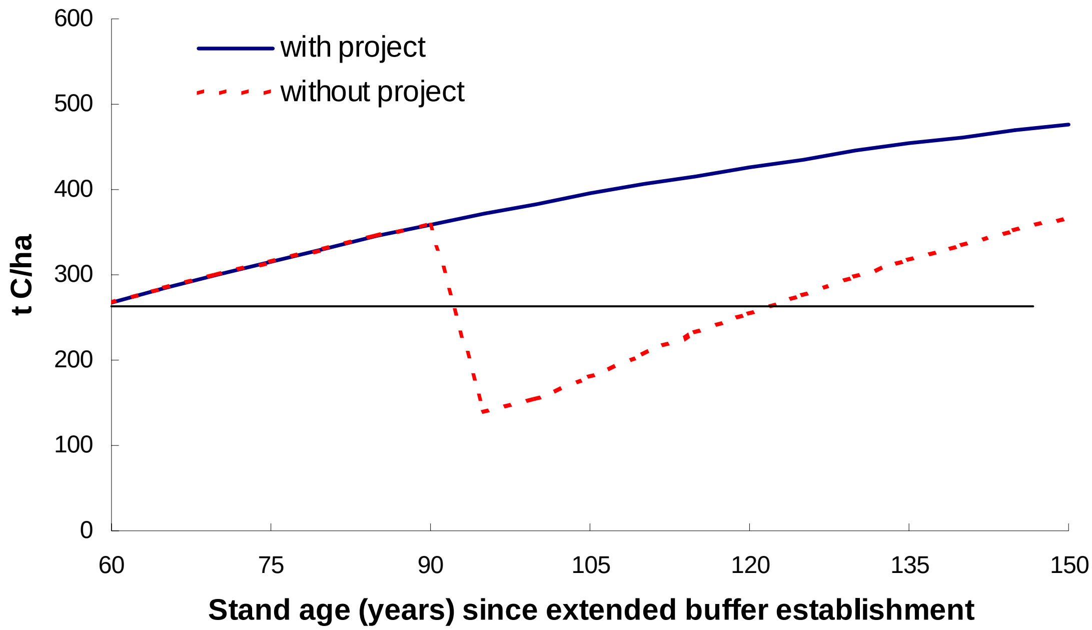

Figure 3.13. Comparative carbon accumulation in extended buffer area with buffer (no harvested) and without buffer (harvested) with initial stand age of 60 years on site index 160 with moderate levels for down dead wood and forest floor. Without project (with harvest) rotation length (90-year) average carbon storage in all pools, including long-term wood products, is 275 t C/ha.

Table 3.4. Comparative total carbon storage (t C/ha) of with (with-project) and without (without-project) harvest in extended buffer cases over a 90-year project period. With-project values equal total forest biomass accumulated at the end of the period. Without-project values equal average carbon storage, including harvest-derived pools of slash and long term wood products, derived for the same 90-year period.

	Site index 120		Site index 160		Site index 180	
Initial stand age	With project	Without project	With project	Without project	With project	Without project
30	**319**	**168**	**426**	**238**	**489**	**296**
60	**371**	**196**	**477**	**275**	**545**	**339**
90	**408**	**221**	**515**	**307**	**586**	**378**

3.5. Carbon benefits

3.5.1. Riparian protection—extending the forested buffer

Over one rotation, carbon storage benefits resulting from extension of the riparian buffer area range from 151 to 208 t C per hectare or 921 to 1,269 t C per one kilometer straight length of stream. Benefits increase slightly with site productivity and with initial stand age.

For a more refined analysis, the contribution of the harvest-derived pools is considered separately. The addition of post harvest slash and long term wood products to carbon storage, which approaches an average of 110 t C/ha derived after 500 years, does not offset the reduction in long term average *forest* carbon storage accompanying management, ~ -300 t C/ha (~ 500+ t C/ha for a mature redwood stand on site index 160 *minus* the long-term average of 193 t C/ha for the same redwood stand under even-aged management with a 90-year rotation) (Figure 3.14). The extended buffer thus offers an unambiguous increase in carbon storage that approaches 200 t C/ha on a time scale of hundreds of years.

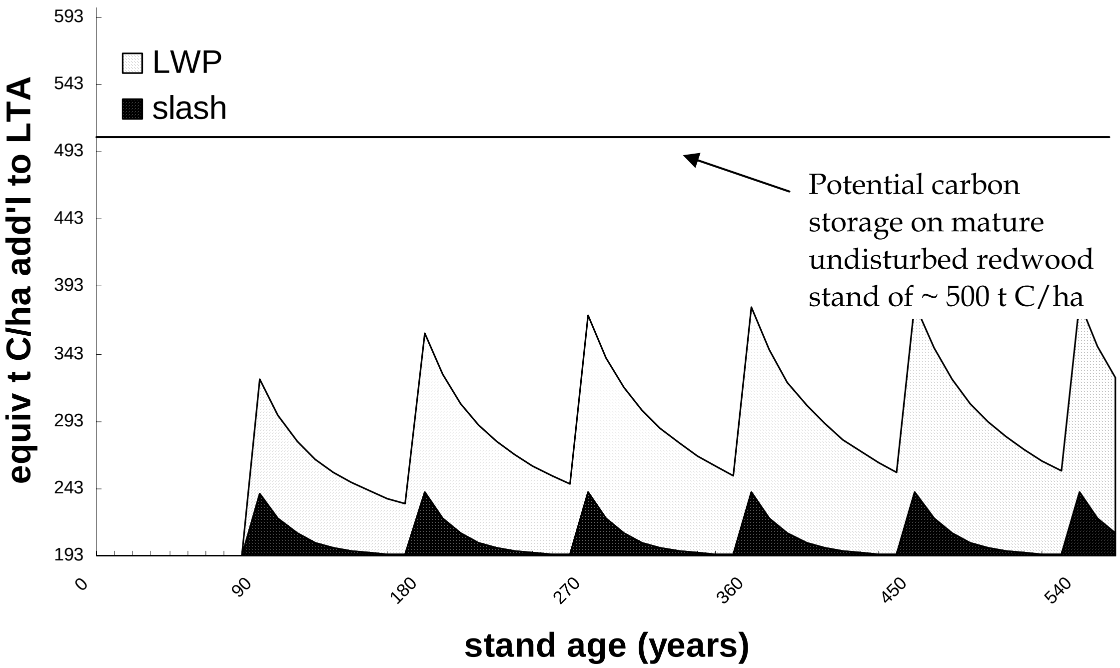

Figure 3.14 Projected accumulation of stored carbon (equivalent t C/ha) in long-term wood products (LWPs) and post-harvest slash additional to the long term average (LTA) forest biomass carbon, 193 t C/ha, for a redwood stand on site index 160 under even-aged management with a 90-year rotation

The estimates provided here are assessments of the potential carbon benefits from extending riparian buffer zones. In this report we have outlined details of the measurements and the types of analyses needed to calculate the with- and without-project carbon stocks when there are existing inventory data and how to consider the variance in calculating the number of plots required for measuring and monitoring (see Appendix A). Where there are no existing inventory data additional measurements would be required but the analyses would essentially be the same as those given here. In a separate report we will provide more details on the methodology for collecting the field data.

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Appendix A: Variance and Number of Plots

The number of measurement plots and consequently the costs of measurement and monitoring are a consequence of desired precision and the variance in the carbon pools.

Typically precision is set at about ±10% of the mean, with 95% confidence; however, precisions as low as 20% or as high as 1% or 2% may be selected. Decisions about precision levels would need to be considered by policy makers and regulators. The 95% level of confidence is usually accepted as desirable, indicating that there is a one in 20 chance that the true value lies outside the interval.

The number of plots is also determined by the variance. When the system is highly variable, in order to capture the variability, more plots will be required. In estimating the number of plots needed to adequately sample a forest, it is usual to determine the variance of the pool where most of the carbon will accumulate, namely in the live aboveground tree pool. The variance may be higher in, for example, the dead wood pool, but live trees overwhelmingly dominate biomass carbon, especially in immature forests, which are the subject of the present study.

Variance changes as forests mature. Young forests have low levels of biomass and often have higher variance. If precise measurements are required at a young age more plots may be needed than if high precision is only required at more mature stages.

In Figure A-1, the number of plots required for given levels of precision is plotted for both mixed Sierran conifer and coastal redwood forests. The source of the data on variance is 80-year-old forest in the BFRS and 100-year-old forest at JSDF. The variance in both forest types is very high. However, the data available here indicate that if 5% precision were desired 289 plots would be required in mixed Sierran conifer forest and 357 plots in coastal redwood forest. If 10% precision were acceptable the number of plots falls to 72 in mixed Sierran conifer forest and 89 in coastal redwood forest.

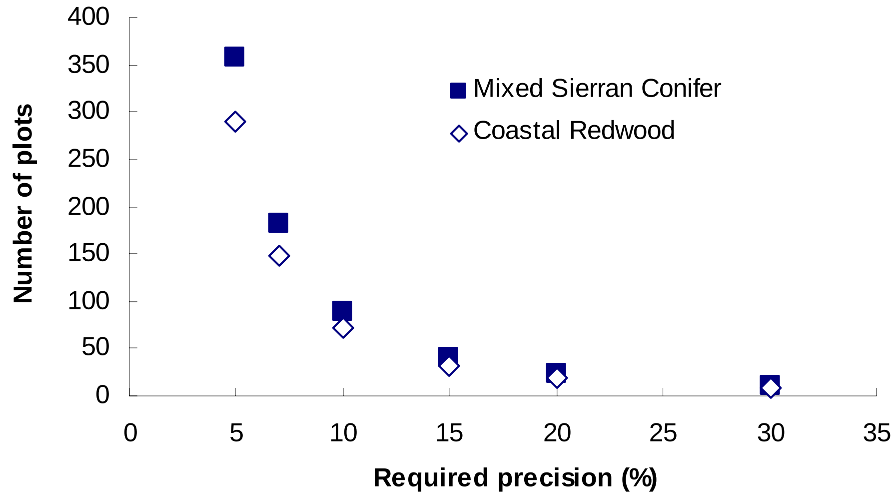

Figure A-1. The Number of Measurement Plots Required to Measure Carbon Density to a Given Level of Precision (confidence interval as a % of mean) in Mixed Sierran Conifer Forest and Coastal Redwood.

The number of plots in these variable west coast sites may be lowered by stratifying the forest sites. Stratifying involves dividing the project into more homogeneous subunits each with a lower variance than the whole. These forests could be stratified according to slope, aspect or species composition.